EXPLORING THE APPROPRIATENESS OF URBAN UNDERGROUND SPACE (UUS) FOR SUSTAINABILITY IMPROVEMENT

By

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ABSTRACT

Due to the dramatic rate of urbanisation worldwide, sustainability of global cities is called into question, and there is global agreement that making cities more sustainable is a key priority. Greater use of underground space is one such solution, hence wider adoption of Urban Underground Space (UUS) within the urban environment needs consideration. One way to measure the efficiency of these solutions within the urban environment is to provide sustainability credentials through sustainability indicators. However, a detailed review of the current 'construction sector' sustainability indicator systems (BREEAM, CEEQUAL, etc.) within this research shows that there is a substantial need for a sustainability indicator tool tailored toward UUS. Hence, a new tool, called USPeAR, is proposed, developed on the basis of the SPeAR® framework system revised and restructured for application on UUS projects.

The USPeAR tool includes a series of indicators based on SPeAR®. They have been selected according to the materiality review method introduced by SPeAR® itself. In addition a panel of experts, who are experienced in terms of construction and sustainability, has been surveyed via a questionnaire to inform the development of an appropriate weighting system for the selected indicators. Lastly, a Cost-Benefit Analysis (CBA) method has been combined with USPeAR to identify the most cost-effective solution for the sustainability improvement of a UUS project. The application of the developed tool was demonstrated through two case studies, in the UK and Iran.

Dedicated to my beloved father

For he has given me the greatest gift one could ask for, he believed in me and always pushed me to believe in myself.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AHP	Analytical Hierarchy Process
BAT	Best Available Technique
BBC	British Broadcasting Corporation
BREEAM	Building Research Establishment Environmental Assessment Method
CBA	Cost-Benefit Analysis
CCTV	Closed Circuit Television
CEEQUAL	Civil Engineering Environmental Quality Assessment & Award Scheme
CUI	Critical Underground Infrastructures
DDPUUS	Development Potential of Urban Underground Space
EIA	Environmental Impact Assessment
GDP	Gross Domestic Product
HalSTAR	Halcrow Sustainability Toolkit and Rating system
ICE	Institution of Civil Engineers
KPI	Key Performance Indicator
LU	London Underground
MRT	Mass Rapid Transit
MUT	Multi Utility Tunnel
NPV	Net Present Value
SAM	Sustainability Assessment Model
SEA	Strategic Environmental Assessment
SEF	Sustainable Economy Framework
SPeAR®	Sustainable Project Appraisal Routine
SWIFT	Structured "what-if" Technique

TAV	Treno Alta Velocita
TLP	Thameslink Programme
UN	United Nations
UUI	Urban Underground Infrastructures
UUS	Urban Underground Space
geoSPeAR	Geotechnical Sustainable Project Appraisal Routine
LEED	Leadership in Energy and Environmental Design
USGBC	U.S. Green Building Council

CHAPTER 1: INTRODUCTION

1.1 Background

Global urbanisation, and specifically growth of urban populations, is a fundamental driver influencing rapid urban development. Based on the world urbanisation prospects in 2014, more than half of the world population lived in urban areas and this figure is expected to rise to 66% by 2050 (United Nations, 2014a). The UK was the first country that exemplified this trend (Clark, 1996), as in the 2001 census almost 80% of the UK population lived in cities, with this figure rising to 90% over the following five years (Denham and White, 2006; UNPD, 2006). Due to this dramatic rate of urbanisation worldwide, urban sustainability has become a core focus of attention in the global environmental debate. Yet unsurprisingly, the sustainability of our cities is not a new aspiration. For example, since the dawn of civilisation, people have intervened in both the nature and form of urban areas to achieve particular social, economic or environmental objectives (Sterling and Godard, 2000; Bobylev, 2009). This activity is known as planning and over the last century, urban planning, of which underground space forms an integral yet often neglected part, has become a discipline and profession in its own right. In this way, urban planning has become institutionalised as a practice of government as well as an activity of ordinary citizens and businesses, and has evolved as a complex set of ideas, which guides both decision-making processes and urban outcomes. Actions taken today are many and varied and much research is taking place to assess the sustainability of these current activities, looking at possible benefits and future trends (see for instance Cooper et al., 2009 and Rogers et al., 2011)

Urban populations and cities around the world will continue to grow, and when coupled with concerns such as climate change, this will affect the basic elements of life for people; this includes: health, food production, access to clean water and energy (particularly for heating and cooling), waste production (and its removal) and the subsequent impact from and to the environment in which we live. Over the last 100 years, in particular, these pressures have led to an ever-increasing demand for both land and infrastructure, which require more appropriate use of Urban Underground Space (UUS). This includes, but is not limited to, Mass Rapid Transit (MRT) and essential networks for distribution of water, gas, electricity, liquid and solid waste (i.e. sewers, pneumatic refuse disposal) and communications. Moreover, the trend is for this demand for UUS to grow even further and in so doing this could contribute significantly (either positively and negatively) towards the overall sustainability agenda (Laistner, 1997; Hunt et al., 2008; Sterling et al., 2012).

In addition, the ongoing pressure between surface land urbanisation and the requirement for more 'space' has led to the increased use of UUS, as a valuable non-renewable resource (Wang et al., 2013). However, with the dramatic rate of urbanisation worldwide, UUS utilisation has reached an unprecedented level and many problems now ensue therein, such as lack of planning, unreasonable layout and disorderly utilisation (Bobylev, 2009; Sterling et al., 2012). As urban underground space is not a limitless resource, the development of UUS must be conducted carefully taking into consideration a range of stakeholders (i.e. professionals that plan for UUS and ultimately the end-users). To ensure sustainable exploitation of UUS, it is necessary to investigate factors influencing what might be described as 'development potential' of UUS (DPUUS), in other words what exists before excavation and construction (Jefferson et al., 2006; Rogers et al., 2011; Wang et al., 2013) and what might exist after.

1.2 Problem Statement

Underground spaces are used to a great extent and potential benefits therein are being exploited, however, these operations are done without sufficient strategic management. As competition for space below ground increases, the likelihood of conflicts between potential benefits (or existing structures) will increase. Hence, more stringent management of 'underground space potential' is required in order to avoid irreversible waste of resources (Godard, 2004; Maire et al., 2006; Parriaux et al., 2006).

However, little research has been undertaken on the essential role the subsurface plays, as a part of our landscape in a sustainable future. This provides a significant opportunity to fill this knowledge gap. This includes finding feasible underground solutions that might help relieve pressures on the surface. From this point, questions then arise as to how we can incorporate the use of underground space in order to create a more sustainable future, or how we can make robust decisions to achieve the goals of sustainability that will facilitate a move from fragmented decision-making to holistic, whole-system thinking. This is essential if wide-ranging sustainability objectives are to be achieved, and, more importantly, if the achievement of each individual sustainability objective is not to be compromised. The challenge here is how cities incorporate new thinking about a potential third dimension of land use into what they do now, while ensuring that what they do now will provide benefit in future (Rogers et al., 2012).

Numerous sustainability assessment models exist in the literature, however the majority of these are applicable to buildings (for example see Banani et al., 2016), very few relate to infrastructure systems (see Koo et al., 2009) and none specifically relate to UUS assessment (Koo et al., 2009; Bobylev, 2016). Bobylev (2016) adds that a challenge for UUS development has been arguing and promoting its inclusion into urban indicators as well as finding an appropriate approach for doing so. Thus, there is a need for such a system to be developed. That said one should not overlook the fact that there are very good civil engineering assessment tools in existence such as BREEAM, CEEQUAL and SPeAR® (Jefferson et al., 2007; Hurley et al., 2008). These systems can aid the process for developing a framework for UUS use rather than considering development of a completely new system.

Therefore, the research hypothesis is *that currently there is no single indicator system/tool that can adequately advise underground stakeholders (e.g. project developers) of the sustainability aspects of UUS usage.* If the literature review confirms this to be true, the author expects to be able to design a comprehensive tool specific for UUS that can be used to assess its contribution towards sustainability.

1.3 Aims and Objectives

1.3.1 Aims

The overarching aim of this project is *to advise underground stakeholders through development and testing of a sustainability assessment tool consisting of an indicator system, with weightings attached where appropriate, that can be used to evaluate the contribution of underground space usage towards sustainability using a three-pillar approach.*

1.3.2 Objectives

To achieve the above aim, the following objectives were formulated:

- **Objective 1**: To conduct a comprehensive literature review on the potential uses of underground spaces (in urban areas) to gain an understanding of the infrastructures that can be built underground;

- **Objective 2**: To investigate, as part of the critical literature review, the relationship between sustainability and underground space, to identify the impact of underground space usage on sustainability, as well as reviewing the existing methodologies and tools used to evaluate UUS impact on sustainability;

- **Objective 3**: To select the most appropriate framework and create a series of indicators designed specifically for underground space use;

- **Objective 4:** To design a questionnaire methodology in order to obtain a weighting system for the selected indicators;

- **Objective 5**: To apply the indicators and developed weightings from the questionnaire to two case study sites and, based on the findings, compare the application with initial model;

- **Objective 6**: To devise a management strategy (including economic aspect) for underground space utilisation and therefore develop a generic methodology, applicable worldwide, to enable the evaluation of UUS's contribution to sustainability.

1.4 Scope and Structure of the Thesis

The outline of the thesis is summarised in Table 1.1.

Table 1.1: Structure of the thesis

Chapter	Title	Content
1	Introduction	This chapter contains the research background, problem statement, aims, objectives, scope and structure of the thesis.
2	Literature review	This chapter addresses Objectives 1 and 2. In this chapter, a thorough review of underground space use in a sustainable urban development, as well as review of current sustainability indicator systems, is presented.
3	Methodology	This chapter supports Objectives 3 and 4. It provides the methodology undertaken for the research.
4	Development of sustainability assessment tool	This chapter addresses Objective 3. It contains a comprehensive review of the SPeAR® tool and introduces a new sustainability evaluation framework, the 'USPeAR' tool specifically for underground space use.
5	Data collection and analysis	This chapter addresses Objectives 3 and 4. It discusses the approach that has been taken to design and establish the tool including the questionnaire design.
6	Case study	This chapter addresses Objective 5. It presents the case study areas and their developmental history relevant to UUS use. The chapter outlines the practical application of the tool to two 'live' case studies.
7	Discussion and recommendations	This chapter provides the discussion of the thesis and addresses Objective 6 by generating a comprehensive strategy for extensive use of UUS and describing its potential benefits.
8	Conclusion	This chapter contains the conclusion of the research and recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

This chapter addresses the first and second objectives of the research by providing a critical review of the literature base related to the following areas: UUS, which includes historical development and the future; critical uses of UUS and the potential benefits provided by UUS usage. In addition, the chapter provides a contextual introduction on sustainability definitions and explores the relationship between underground space and sustainability. Finally, the chapter reviews existing sustainability assessment tools and identifies then discusses their application for UUS assessment.

2.1 Background

Urban sustainability has become a core focus of attention in the global debate around population growth and resource scarcity, and is one of the major concerns of modern societies (Koo et al., 2009; Lombardi et al., 2012). A comprehensive assessment of sustainability has become crucial to measure progress, identifying areas to be improved and evaluating policy outcomes, hence the need to find measures to translate sustainability into a series of approaches and indicators, which can help implementation of developments (Pinar et al., 2014; Bobylev, 2015).

With the dramatic rate of urbanisation worldwide (54 per cent of the world's population residing in urban areas in 2014) (United Nations, 2014a), underground utilisation has reached an unprecedented level and many problems now exist that stem from lack of planning, unreasonable layout and disorderly integration (Bobylev, 2009; Sterling et al., 2012). Many authors have concluded that currently, underground space exploitation is in an unfavourable situation, and it exists because the space below ground is not visible, and therefore it has for too long not been possible to guarantee sustainable performance therein (Jefferson et al., 2006; Lee et al., 2016; Zhao and Künzli, 2016).

Hence, the development of underground space must be conducted more carefully and professionally. To ensure the sustainable exploitation of underground space, it is necessary to investigate factors influencing the development potential of urban underground space before excavation and construction is undertaken (Jefferson et al., 2006; Rogers et al., 2011; Wang et al., 2013).

2.2 Urban Underground Space (UUS)

2.2.1 Historical development of underground space

Historically, our surrounding urban environment has principally been a two-dimensional space (i.e. the ground surface area – with outward and upward expansion), where underground exploration has been adopted only by necessity, curiosity, or even through fear as a hiding place for primitive populations (Sterling and Godard, 2000; Parriaux et. al., 2007). However, the scale of cities has not been able to grow infinitely upwards at the surface due to the length and complexity of structures, while urban sprawl is understandably limited through highly regulated land use planning in order to maintain ecological equilibrium (Parriaux et al., 2007). In order to overcome these limitations, a considerable amount of effort has focused on utilising the third dimension - downwards expansion (Sterling and Godard, 2000). However, underground works are not straightforward and have always encountered difficulties (Sterling and Godard, 2000), such as a lack of mechanised equipment or insufficient knowledge about previous land uses (Bergman, 1986). In order to facilitate discussion of the attempts to exploit underground space, throughout this study, 'underground' or 'subsurface' will refer to any surface located below ground level, whilst the term surface space refers to any space above ground level, following the terminology used by Rönkä et. al., (1998) and Evans et al., (2009).

The history of subsurface use goes back to the Neolithic age when underground passages served as a hiding place for primitive populations (Sterling and Godard, 2000). In addition, there is evidence of underground excavations that belong to the first stages of human development – these were used as dwellings and for food storage purposes (Sterling and Godard, 2000; Bobylev, 2009). During the 16th Century, underground chambers were exploited as a means of finding relief from hot weather in many cities around the world. Palermo city in Italy is one such example (Polemio, 1996). Another example is the construction of the Bazalgette sewer system in London, started in 1858 and completed in 1865. Through a series of collection sewers and pumping stations wastewater was conveyed from the streets and discharged to the Thames (Lofrano and Brown, 2010). However, it was not until the late 19th Century that new doors were opened to a much broader range of uses for UUS that included more types of utility: gas, electric, water and communications; and transport infrastructure (Carmody and Sterling, 1993). An example is, advancement of MRT around the world following the lead of the London Underground railway which opened in the UK more than 150 years ago. In the 20th Century, significant advancement in construction technologies resulted in a boom in UUS development, i.e. MRT and other recent fields such as the development of hydroelectric facilities and even the utilisation of pore space in sedimentary rocks to store gas and fluids (Sterling and Godard, 2000; Bobylev, 2009; Evans et. al, 2009). For centuries, considering the above reasons, underground space was an important resource exploited for the construction of structures for everyday use (Evans et al., 2009).

There is an abundance of reasons why early man and even more so modern-day city planners and engineers seek to capitalise on the many benefits offered through underground space usage. This includes, but is not limited to, provision of space for storage, natural protection and isolation (Sterling and Godard, 2000). Throughout history, the subsurface has been extensively quarried and mined for resources utilised for human activity. The earliest underground usage refers to the tunnels that were in fact, caverns, man-made cave dwellings for human habitation and even galleries adorned with artwork (Sterling and Godard, 2000).

2.2.2 World population and the future of UUS

The quest for more space in large urban areas is a global phenomenon (Admiraal, 2006; Makana, 2014). By 2009, more than half of the world population was living in urban centres and this is predicted to increase rapidly (and continually) into the future (Chow et al., 2002; Besner, 2002; Parker, 2004). Most of this growth is happening in developing countries where cities are being challenged by the need to meet increasing demands for basic services (e.g. infrastructure, jobs, land, and affordable housing). This is particularly true for the nearly one billion urban poor who often live in informal settlements; that organically grow in order to enable more inclusive development while preventing some of the negative impacts of rapid expansion (World Bank, 2015a). However, an even more alarming fact is that in the future most of the world's population will live in urban areas: As shown in Figure 2.1 it is predicted that by 2030 > 60% or 4.9 billion people will live in cities (United Nations, 2011). As such, the search for more space in urban areas is growing and requires utilisation of underground space – unsurprisingly it is often perceived as the only remaining solution (Admiraal, 2006). This demonstrates that global urbanisation and specifically growth of populations are the fundamental drivers that influence greatly increased use of UUS. This indicates that cities with high population densities at some point in the future cannot avoid development of their UUS, and according to several authors, this is a reasonable assumption (Horvat et al., 1998; Chow et al., 2002; Evans et al., 2009).

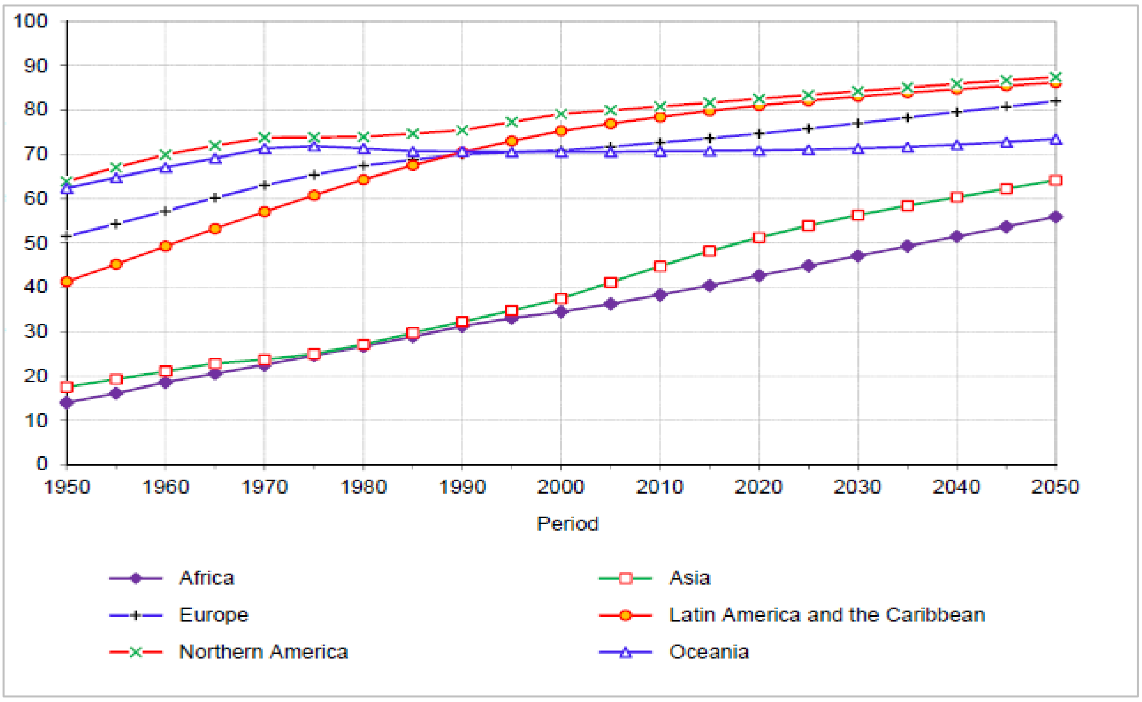


Figure 2.1: Urban population by major area (in % of total population) (United Nations, 2011)

Based upon the information shown in Figure 2.2, it can be seen that the UK exemplifies this trend in Europe (Clark, 1996; United Nations, 2014b). As a result, new infrastructure systems (e.g. HS2 and HS3) must be constructed not just for these cities to become more sustainable, but more importantly just for them to survive. Many authors suggest that underground construction could / should be the preferred method of choice for much of this essential infrastructure (Carmody and Sterling, 1993; Cano-Hurtado and Canto-Perello, 1999; Rogers and Hunt, 2006; Bobylev, 2009; Canto-Perello and Curiel-Esparza, 2013; Hunt et al., 2014).

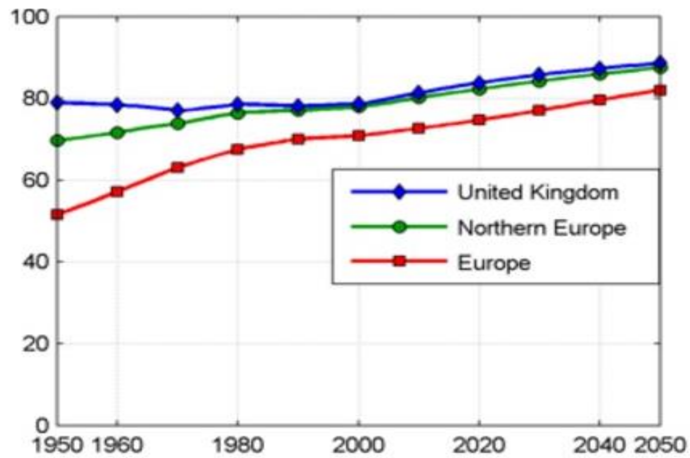


Figure 2.2: Urban population by major area in UK (in % of total population) (United-Nations, 2014b)

Contemplations in regards to the significance of UUS to address urban improvement were raised approximately a century ago by Hénard (1903). These reports with respect to the significance of UUS have since been re-examined by a range of authors and institutes (e.g. Utudjian, 1952; Utudjian and Bernet, 1966, Fairhurst, 1976, Duffaut, 1977, Carmody and Sterling, 1993 and Godard and Sterling, 1995). The most recent discussions include Hunt and Rogers (2005); Jefferson et al., (2006); Parriaux et al., (2006); Rogers and Hunt (2006); Simpson and Tatsuoka (2008); Bobylev (2009); Sterling et al., (2012), collective works by the International Tunnelling Association (ITA), 1970-2014, Bobylev (2016); Hunt et al., (2016); Makana et al., (2016); Admiraal and Cornaro (2016a,b); Broere (2016) and Besner (2016).

Urban areas, during the next four decades (i.e. up to 2050), are projected to absorb most of the world's population growth (Figure 2.3), while at the same time drawing in some of the rural population, hence densification (i.e. smaller land mass area allocation per head of urban population) is likely to occur (United Nations, 2014c). As such, greater consideration is required as to how available space (i.e. that which resides above and below ground) is used and how city resources are conserved (Goel et al., 2012).

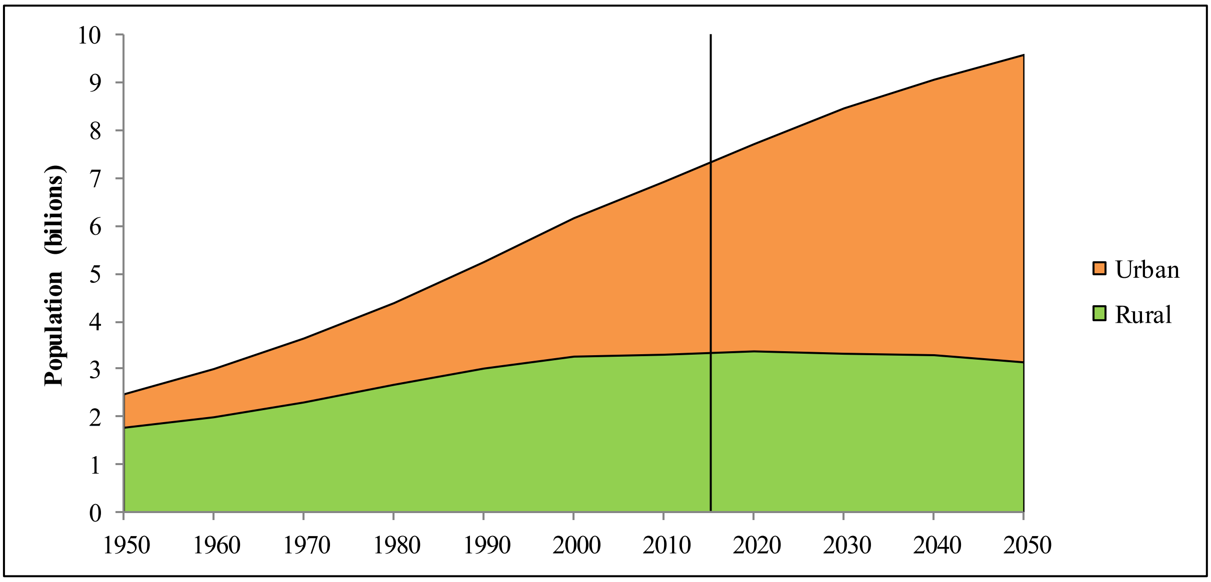


Figure 2.3: The world's urban and rural populations, estimated for 1950-2014 and projected to 2050 (United Nations, 2014c)

A typical configuration for an urban space use can be represented by a normal, or Gaussian, distribution. Space use can take the form of the usual arrangement indicative of current active utilisation of land in major cities (Figure 2.4a), where the greatest land use occurs at the centre and diminishes on the outskirts, or alternatively can have an inverted dome pattern which incorporates the use of UUS, and is the goal of urban space use planning (Figure 2.4b) (Goel et al., 2012). According to Goel et al., (2012), a Gaussian distribution curve is also a representation of the economic growth of the city, where the centre of city is assumed to be at the middle of the horizontal axis. However, in terms of seeking to create yet more facilities (and, therefore, opportunities) and in order to favour a more compact urban pattern (deemed to be more sustainable), which incorporates more public open space, there is an increasing desire from urban city planners to follow the inverted dome pattern. Hence, in order to meet cities' needs, priority should be given to the development of underground space, as a starting point for reforming current unattractive surface development. In other words, to revitalise cities in which surface space use tends to develop laterally, great importance is now placed on directing urban development towards an arrangement with vertical form i.e. utilising underground space (Goel et al., 2012).

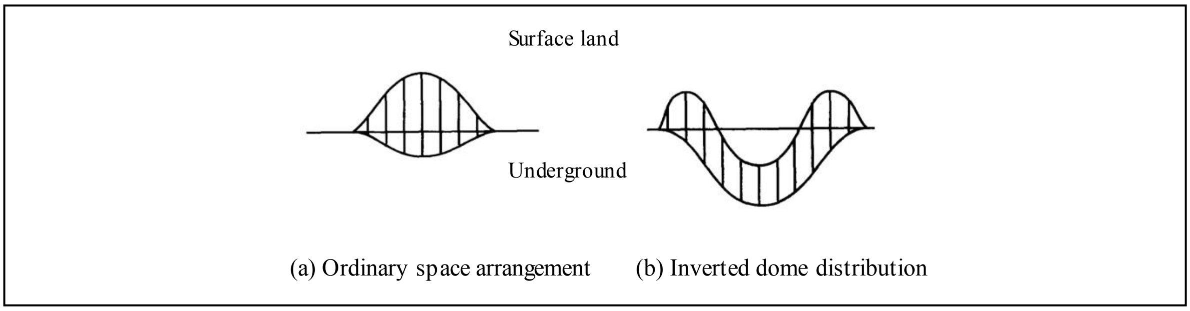


Figure 2.4: Gaussian distribution curve describing urban space use planning (Goel et al, 2012)

Such a development requires increased exploitation of underground space at both shallow and deep levels over greater distances (Watanabe, 1990; Goel et al., 2012). In the following section (Section 2.3) a critical review of UUS exploitation and the various advantages offered is provided.

2.3 Critical Uses of Underground Space

This section will review different Urban Underground Infrastructures (UUI). UUI is defined as a series of underground structures interconnected either physically or functionally (Bobylev, 2007; Sterling et al., 2012). They are mainly divided into two categories:

1) Functional infrastructures (see 2.3.1); which include utilities (water, energy, waste, sewage, and telecom), storage facilities (gas, food and oil) and energy exploitation systems (geothermal boreholes) (Li, 2011). These facilities aim to support urban daily functionality by enabling smooth delivery of resources and residual output, through the city.

2) Passing and living spaces (see 2.3.2); such as transport networks (subway and road tunnel), subterranean stations (parking, subway and bus), and sub-surface recreational centres (shopping centres, sports facilities, theatres, museums and libraries). These infrastructures provide spaces for human activities, which are usually 'passing-through' or short time stays, without disturbance of the outdoor environment (Jefferson et al., 2006; Parriaux et al., 2006).

However, among different uses of UUS in terms of functional infrastructures and passing and living spaces, some of the underground structures are functionally vital for a community; these infrastructures are named Critical Underground Infrastructures (CUI) and it includes, for example, most traditional underground networks such as water supply, wastewater treatment, transport and electric cable tunnels (Bobylev, 2007).

2.3.1 Functional infrastructures

This group of infrastructures is divided in to utilities and storage facilities. These are described as follows:

Utilities (e.g. Water, energy, sewage)

To date, one of the most extensive and essential uses of underground space is allocated to the urban utility systems (United Nation, 2012). Utility services are provided in a wide range, including:

- Gas and water pipes,
- Electricity cables,
- Sewers and storm water drainage, which are sometimes combined;
- Telecommunication cables,
- Fibre optic cables (being particularly vulnerable to damage and expensive to repair);
- Street lighting and traffic lighting cables
- and wires and cables (that transport people, goods, and public services (Canto-Perello et al., 2009).

Utility systems are usually considered as a relatively recent development in the history of humankind, though nowadays life in developed areas is impossible without them (United Nation, 2012). The use of utility tunnels to support urban services goes back to the engineers of the Roman Empire, who placed water supply conduits in the sewage systems. An example of this technology is the sewers of Rome, including a huge cross section, which is still in use. Cano-Hurtado and Canto-Perello (1999) explain the way that this technology was forgotten and how it was resurrected in 1855. Utility systems have also been one of the most extensive uses of underground space and have developed rapidly in urban areas. Water and sewer systems were followed by electricity and telephone systems, district heating systems, mass transit systems and communication systems (United Nation, 2012).

In order to deliver a well-functioning city in the 21st Century, uninterrupted supplies of resources such as energy and water that match demand are required (Hunt et al., 2009). Currently almost all of the countries around the world benefit from underground space for utility use. In essence, underground utilities exist in different forms of tunnels, water and heat pipes and a range of electrical communications (Canto-Perello and Curiel-Esparza, 2001; Canto-Perello and Curiel-Esparza, 2003; Curiel-Esparza and Canto-Perello, 2013). Whilst utility tunnels have been used extensively worldwide they are not always used in the correct way and have not always been placed in locations where it would be most desirable (Canto-Hurtado and Canto-Perello, 1999). Rogers and Hunt (2006) and Curiel-Esparza and Canto-Perello (2013) mention that as underground space becomes scarcer, the need for more co-ordinated and efficient sub-surface facilities (such as utility tunnels) placed in the right locations will be required (McMahon et al., 2005; Hao et al., 2012).

Storage facilities (gas, food and oil)

Man has historically made use of UUS, initially in forms of natural caves as shelter for dwelling and for food storage purposes (Sterling and Godard, 2000; Bobylev, 2009). With time, man started using UUS for other storage purposes including disposal by burial, and a wide range of materials, from energy products such as natural gas and oil to chemical products and waste.

Generally, UUS is capable of providing isolation against the surface climate. The constant temperature within soil or rock along with the natural conditions in dark, cool, humid underground chambers represents a uniform thermal environment unaffected by extremes of surface temperature (Tatiya, 2005). Moreover, these moderate temperatures and the slow response of the large thermal mass of the Earth offer significant advantages in terms of storage and preservation of objects and products stored within the structure (Carmody and sterling, 1993; Sterling and Godard, 2000; Godard, 2003). Traditionally the wine cellar has been one of the most extensive uses and remains popular. For example, the use of caverns for ageing wine has been regular used in many regions such as France (Carmody and Sterling, 1993).

On the other hand, oil and gas caverns could be considered as two of the most essential elements in the fuel supply of all industrialised countries in both economic and military terms. Therein, it is of great concern to insulate the supply (not least domestic) from seasonal problems or international shortages (e.g. through underground stockpiling). To achieve this, a great number of oil and gas storage systems have been built underground around the world (Carmody and sterling, 1993).

2.3.2 Passing and living spaces

This category is classified under transport networks and recreational use, which are described further below:

Transport network (subway or road tunnel)

With the growth of population worldwide especially in dense urban centres, cities have found the need to develop and improve UUS transportation systems in order to help solve a number of arising problems, such as (and not limited to) traffic congestion, noise and air pollution. ITA (1987) states that mobility is essential to human activity and further explains that the history of human-development (and their needs) represents this case perfectly. Initially the first towns were built, at either a major crossroads or waterways, where people wished to exchange goods and ideas and meet, the local authorities accordingly always did what they could to encourage this through mobility investment because they recognised how important it was for the social, cultural and economic development of their cities (ITA, 1987). One way to improve mobility has been through the use of tunnels. The earliest evidence of tunnelling dates back to about 15,000 years ago, when horse bones were used to dig tunnels for mining flint. However, it was in 1600s, when the speed of tunnelling in rock increased greatly and permitted a wider range of uses (Carmody and Sterling, 1993). As cities have expanded, and tunnelling methods have continually been improved, more and more tunnels have been used for urban transportation systems, this includes rail subways, motor traffic tunnels and utility tunnels. London's metropolitan railway was the world's first subway (6 km length) opened in 1863 and ran between Paddington and Farrington (Carmody and Sterling, 1993). A study by Bobylev (2009) in three cities – Paris, Tokyo and Stockholm (Figure 2.5) shows an example of widespread use of UUS based on utilities, transport and other uses such as public spaces, shopping areas, car garages, storages and industrial use. The study revealed transport and utilities to be the most common functions of UUI.

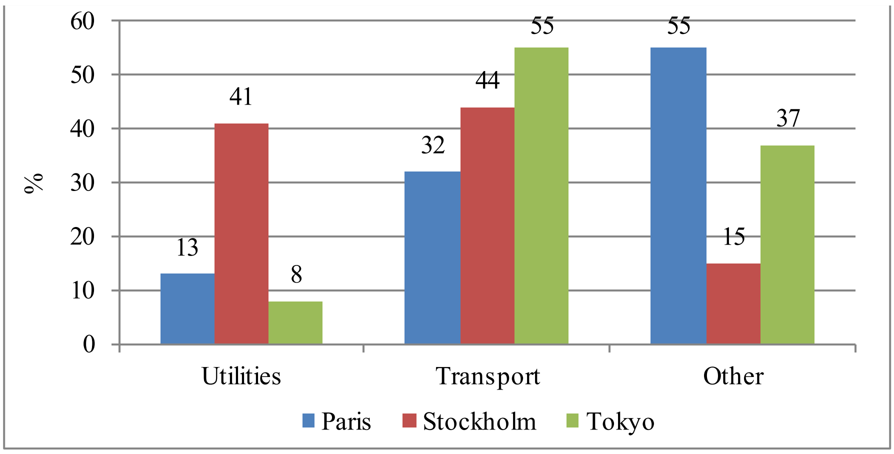


Figure 2.5: UUS use by function (Bobylev, 2009)

Subterranean stations (parking, subway and bus)

Traffic congestion is a serious issue in all mega cities (Goel et al., 2012) another is parking spaces for all the cars. A solution is subterranean parking stations. Construction of underground parking facilities has increasingly drawn attention as a solution for parking problems in many urban areas (Hunt et al., 2016). This is particularly well-suited where there is a pre-requisite to allocate parking spaces nearby to activity sites without disturbing space above ground. This often leads to an underground solution even when those funding the development know that underground parking accounts for several times the cost of surface parking. Whilst many open spaces in city centres appear to be unused they are underlain by parking facilities with un-obtrusive entrances. Since there is a huge cost with excavation on crowded urban sites, car parking is usually made as dense as possible. In drive-in ramps- two level parking machinery may be used to increase density. Automatic parking facilities have also been used in Europe to increase density and remove a major operational cost of conventional underground parking-forced ventilation for the enclosed structure (Carmody and Sterling, 1993). Underground car parks solve many of the traditional problems associated with urban parking congestion, pollution, land space, and security (Goel et al., 2012).

Recreational use (Shopping centres, sport, theatre)

During the last 50 years, different premises have been moved underground in order to either provide more facilities in densely built up areas, or to provide a more desirable environment above ground (Vähäaho, 2011). A great range of facilities such as sporting venues, communication centres, cinemas, theatres, libraries, shopping centres and even surgery rooms can be built below ground. In these premises, the aim is to provide a feeling of space using good artificial lighting instead of direct sun light. One of the examples is the underground city of Helsinki in Finland. In this underground city, there is a church called Temppeliaukio, which is one of the most popular tourist attractions receiving about 400,000 visitors a year (Vähäaho, 2011). Quarried out of solid rock, it can be converted into an emergency shelter for 3,800 people if necessary (Vähäaho, 2011).

As well as this, Itäkeskus swimming pool is located below ground and is one of Helsinki's underground recreational facilities. Its facilities are on two floors and it can accommodate about 1,000 visitors at a time. Another example is the British library in the UK, with a 23m deep basement storing nearly 12 million volumes (Bank, 2009) or even an underground school facility in the Netherlands as shown in Figure 2.6 (Admiraal, 2006).

Figure 2.6: Underground school facility, Arnhem, The Netherlands (Admiraal, 2006)

Another interesting example is in New York (NY) where frustration by the lack of space above surface has seen innovative use of UUS emerge (Hunt et al., 2016; Admiraal and Cornar, 2016b). Traditionally in NY it has been upward building, but this city renowned for its skyscrapers is now looking to utilise underground space too. The Lowline (Figure 2.7) is a proposed subterranean park the size of a football pitch that would be created on the site of a former trolley terminal in Manhattan's Lower East Side (Admiraal and Cornaro, 2016b; Hunt et al., 2016). It is planned to provide adequate lighting from use of solar tubes and fibre optics from above surface to the terminal (Admiraal and Cornaro, 2016b).

Figure 2.7: Lowline underground park (Admiraal and Cornaro, 2016b)

2.3.3 Critical Underground Infrastructures (CUI)

According to Bobylev (2007), CUI comprises underground critical networks that support a city (categorised as either "functional" or "passing and living" infrastructures), such as utilities in terms of water supply and electric cable tunnels, transport and wastewater treatment. Utilities have been reviewed in Section 2.3.1, and transport in Section 2.3.2. In this section, wastewater treatment is discussed.

Wastewater treatment

One of the essential infrastructure services for human survival (and prosperity of the economy) is the provisioning of clean water. As a finite resource that is continually in use (and reuse) in the water cycle (including natural and manmade processes, the size of this infrastructure system and ultimately the impacts on human life are significant (Koo and Ariaratnam, 2008). Therefore, it needs to be carefully protected and planned for. This becomes even more important when, by 2050, it is predicted that the world will be facing a water scarcity due to the growth of population (Henriques et al., 2015).

Wastewater treatment is relatively recent practice in the last 150 years. However, underground sewers used to remove foul-smelling water were common even in ancient Rome, though their use was not extensive until the 10th Century. Despite the natural characteristic of water to cleanse itself over time, the population had become so concentrated that by 1850 water-borne disease carried by polluted water was becoming a threaten to city dwellers (Carmody and Sterling, 1993). Larger cities realised the necessity to lessen the amount of pollutants in the untreated discharged wastewater within the urban environment. Since then the practice of wastewater collection and treatment has been perfectly urbanised by means of a range of techniques. An example is the central wastewater treatment plant for North-Jaeren region in Norway (Ronning, 2006). In addition, Helsinki provides a second example of where UUS was used to locate wastewater treatment plants, in around 1910. New plants were progressively added to the system as the population grew (Käimppi, 1994).

2.4 Underground Space Resources

According to the "ecosystem services" definition, nature is a resource that offers specific services to human beings, such as drinking water and protection from solar radiation (Bobylev, 2009). However, these services are in danger of being effected by social impact and global environmental variation. Similarly, the idea of "ecosystem services" can be applied to UUS; deliberated as an area rich in resources (Admiraal, 2006). UUS provides certain services and offers various benefits for different purposes / functions. Therefore, it is of great concern that planners identify the importance of UUS, allocate a value to that function and consider it more readily in the land-use planning and within the process of developing a long-term plan. Therein a strategic vision should consider the role of UUS services during planning processes with specific reference to services that might be related to future urban development and sustainability. Parriaux et al., (2008) and Bobylev (2009) identified four categories of resources related to use of UUS (see Figure 2.8). Explanatory text follows.

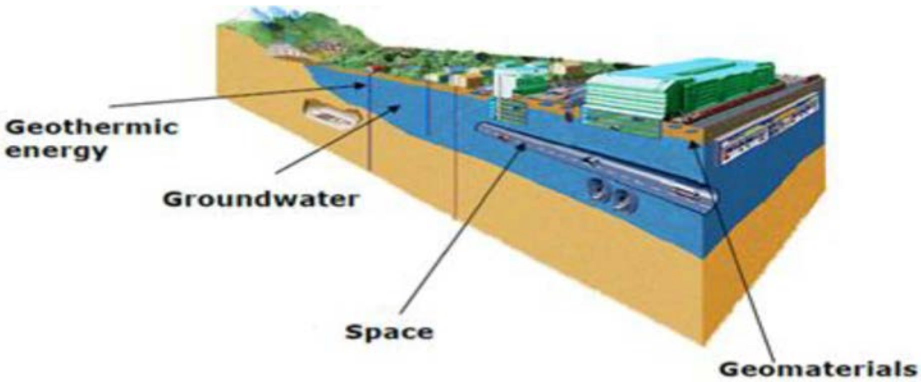


Figure 2.8: Underground resources (Parriaux et al., 2008)

i. Space resource:

Land above ground is limited and in some respects a non-renewable resource. On the other hand, land underground is another exploitable dimension, which can offer many more possibilities for construction and a different range of uses, such as subway tunnels, road tunnels, buried utility lines, subterranean parking, deep storage, pedestrian passes, and large basement buildings (Bergman, 1986). Moreover, going underground can relieve the pressure on the surface, from building height limits and from landscape control (Carmody and Sterling, 1993; Golany and Ojima, 1996). In addition, the space and volume of the underground could help to reduce densification above ground and provide much needed urban revitalisation.

ii. Water resources (i.e. underground water aquifers):

Water, is a critical production element for agriculture, industry and urban development. The utilisation of groundwater amounts to more than 70% of overall water consumption (mainly for domestic drinking water purposes) in the majority of European countries (Zektser and Lorne, 2004; Makana, 2014). Groundwater is a critical natural underground resource that is coupled to the local and global hydrological cycle. Moreover, variations in groundwater conditions (e.g. through groundwater abstraction) need to be monitored and understood not least when considering the disturbing impact this can have for above ground structures. Also, groundwater pumping can lead to geotechnical conflicts for underground infrastructures, namely land subsidence caused by overexploiting groundwater. As a result, this is one of the resources of underground (Li et al., 2013a).

iii. Geo-material resources:

Accessibility of materials (i.e. aggregates which can be extracted from underground excavation and expended for city development) is one of the principle elements affecting construction activities, either above or underground. As mining and quarrying activities become more limited, delivery of raw materials has grown to become more challenging. A recyclable material source, from construction excavation sites of urban underground, could relieve material provision deficiency (Li et al., 2013a). In other words, waste generated from underground construction, such as rock, sand, etc., can be reused and recycled as new raw materials. This has been an economical solution to recover excavation cost too (Li et al., 2013a).

iv. Geothermal resource (shallow and deep geothermal systems):

Energy supply is a challenge to modern societies. Transportation and building energy requirement account for more than half of the total energy demand. Geothermal resources basically extract heat from UUS and this could be used to partially meet heat demands. [N.B. Retrieving energy stored in UUS requires active heat conversation using ground source heat pumps (IEA, 2010; Hunt et al., 2016).]

Bobylev (2009) furthermore divides UUS resources into:

- Renewable vs. non-renewable services and resources (Figure 2.9);
- Passive vs. active utilisation of services and resources (e.g. groundwater supply for surface vegetation in contrast to drinking water supply).
- The amount of 'competition' and/or 'elimination' of the utilisation of services and resources (i.e. can various services coincide or does use of UUS for one prior service or resource prevent other potential uses of UUS; e.g. 'cultural heritage' which can prevent an area of unique geological value from being excavated).

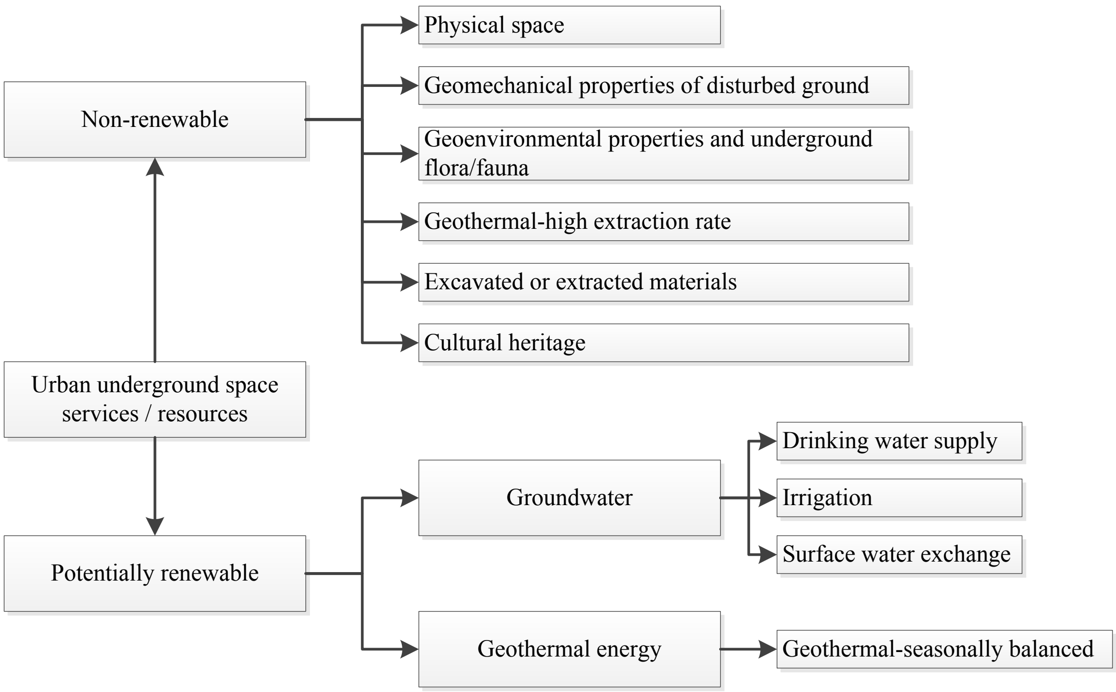


Figure 2.9: Renewable and non-renewable UUS resources (Bobylev, 2009)

2.5 Sustainability

It was not until 1987 that the World Commission on Environment and Development (WCED) proposed the term 'sustainable development' for the first time. WCED was organised by the United Nations in 1984 and, for three years, they attempted to reach a comprehensive understanding of the existing conflicts between increasing global environmental problems (e.g. pollution arising from resource extractions or industrial processing, transportation and from wastes generated by humans) and the needs of less-developed nations (Parker, 2004). The findings reported in 'Our Common Future' Report, often called the Brundtland Report, proposed the term *sustainable development* (Brundtland, 1987). The report defines sustainable development as:

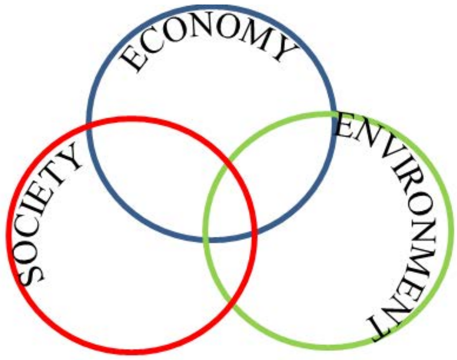
"*A development which meets the needs of the present without compromising the ability of future generations to meet their own needs*."

In other words, sustainable development is that which incorporates a delicate balance between economic growth, quality of life and environment, whilst ensuring that the needs of our future generation are met (Parker, 2004).

Sustainability is a challenging, open and contested concept (Gladwin et al., 1995; Giddings et al., 2002; Banerjee, 2003; Parris and Kates, 2003; Elliott, 2012; Makana, 2014). Though represented as a contemporary ideology, it is, in reality, embedded in what engineers have always been trying to do (Rogers, 2009). These ideas are reinforced with an example whereby engineers are expected to provide access to clean and hygienic living conditions through supplying clean water, sewerage and a range of waste disposal systems. Then again, as urban societies have started to expand, energy is being provisioned remotely via utility infrastructures, so that streets in our urban environment now accommodate a complex set of service pipes and cables (Rogers, 2009).

Normally, principles of sustainability within a development or organisation are evaluated through a 'three-pillar' method (see Figure 2.10a) incorporating economy, environment and society, which are evaluated alongside each other rather than ignoring (or preferencing) one over another (Jefferson et al., 2006). However, some authors such as Giddings et al., (2002), Jefferson et al., (2006) and Rogers, (2009) report that, in reality, the distinctive element central to the assessment of sustainable development is its environmental performance. This is known as the embedded, or nested, model (Figure 2.10b). Giddings et al., (2002) states that economy and society are interconnected in their existence, but both cannot exist without environment, and, therefore, suggest that any assessment of sustainable construction should start from environmental aspects. Mulligan (2015) has interpreted embedded model as one which considers economy within the social aspect, and both under a wider category of environment.

Mulligan (2015) explains that the unwanted impact of this model could be to consider the economy as the starting point of sustainability considerations, with society and the environment remaining in the background. Even though this focus on the economy might be realistic, the author criticises such a model for demonstrating an inflexible relationship between the three pillars; whereas the three-pillar approach allows for the opportunity for needs and considerations to come up separately within any of three pillars before they are brought into interaction with each other. Mulligan (2015) adds that, all in all, no model is perfect when considering sustainable development, and that the existing interlinkages between economy, environment and society require the simultaneous consideration of the three sustainability pillars in a conceptual, as well as in a quantitative, way. Hence, to achieve a sustainable design, all three of these pillars (environmental, economic and social) must support and be supported by the others (Mihelcic et al., 2003; Kaminsky, 2015; Rodríguez-Serrano et al., 2017).



(a)

(b)

Figure 2.10: (a) Conventional (b) embedded sustainability model (Jefferson et al., 2006)

However, according to Rogers (2009), the three-pillar model is a conceptual model only and many would criticise it for a lack of efficiency in certain situations, and would advocate that construction, by its nature, is unsustainable; so it is not surprising in some cases to add a fourth pillar to provide the appropriate balance. For example, cultural vitality, good governance and political frameworks have been suggested for inclusion (Hawkes, 2001). Resource use is also included within the UK sustainable development strategy framework indicators (Rogers, 2009; Jefferson et al., 2009). Alternatively, authors such as Parris and Kates (2003) and Keiner (2005) reported institutional sustainability as a fourth pillar for construction purposes, while Kaminskky (2017), who has investigated sanitation infrastructure construction, suggested technical performance as the fourth pillar.

However, as there is no global model for sustainability, these different conceptualisations of the fourth pillar will need to be refined, taking into account local geography, culture and context (Rogers, 2009). Hence, in the light of the literature, and bearing in mind that the aim of this research is to develop a globally applicable tool, the author came to the conclusion that a simple attempt to envision the future by way of illustration of the above points, would be to take the three pillars in turn. It was, therefore, decided not to consider a fourth pillar in this research study. This decision was also made to simplify the required model for potential users, as the three pillars are better known and generally agreed upon.

2.5.1 Relationship between underground space and sustainability

A definition for underground space is presented by the American Underground Space Association as *'a certain volume of resources that are naturally or artificially raised beneath the surface of the ground within a range of agreeable usage*'. The shortfall of this description is that it only includes physical features and is according to a superficial concept – for instance, how to measure 'agreeable usage' and to whom does this relate (Bobylev, 2016). Hence, we need to have a clear understanding of the overall characteristics of underground space in order to lead us to strategies for its effective application. In this respect policy makers are urged to address recent issues (e.g. lack of space) that highlight the need for UUS and its corresponding features that differentiate it from other city strategies (Bobylev, 2016).

Modern life has embraced the advantages of underground spaces and in today's society almost everyone has, to some extent, benefitted from them. UUS plays a dominant role in maintenance and / or raising our standard of living whilst preserving the environment, at least within developed countries (Hanamura, 1998). UUS has certain natural characteristics generally referred to as the main reasons for going underground (Besner, 2002; Parker, 2004; Bobylev, 2009).

Sterling et al., (2012) discuss some possible catastrophic events that also might lead to UUS being beneficial. For example, one benefit is the isolation provided by the covering soil or rock from events that occur on the surface. Another is excellent resistance to events such as hurricanes, tornados, external fires, external blasts, radiation and other terroristic threats (Lindblom, 1990; Parker, 2008; Sterling and Nelson, 2013) For example in the event of floods and hurricanes, external fires with the provision that access points are secured and / or sealed, the forces on geo-structures are clearly known and simply dealt with when weighed against the impact, flood and wind loadings for surface structures (Canto-Perello and Curiel-Esparza, 2001; Canto-Perello and Curiel-Esparza, 2003). Section 2.5.2 reviews these in more details.

2.5.2 UUS characteristics with respect to three pillars of sustainability

Given the wide range of underground structures, each will contribute to improving the sustainability of an urban environment in many different ways. Each pillar of sustainability is considered in turn below:

2.5.2.1 Environment

Underground space is abundant and opaque and provides a range of advantages in these terms. For example, the underground protects against external influences and provides adequate isolation against surface climatic conditions (e.g. extremes of heat, cold and rainfall). Likewise, the surface is to some degree protected from environmental impacts (e.g. noise, air pollution and green gas emissions) arising from within facilities located underground, and these are significantly reduced as compared with those facilities located above ground (Carmody and Sterling 1993; Sterling and Godard, 2000; Sterling et al., 2012). Underground facilities can help to reduce atmospheric emissions directly or indirectly, either by reducing daily transportations due to the shorter distances they provide or by reducing traffic congestion at the surface (Bobylev, 2006 and Sterling et al., 2012). Additionally, from an environmental aesthetic point of view, underground structures are less visible than surface structures hence their visual impact is significantly improved. This consideration is becoming essential when it comes to hiding facilities such as utilities, which are not desirable to be on the surface in particularly sensitive locations, for example, in close proximity to residential urban areas, environmental impacts should always be minimised due to the increased risk of exposure (Bobylev, 2006; Sterling et al., 2012). With this in mind, there are different assessment methods that can deal with environmental issues linked with underground infrastructures (Bobylev, 2011). The most commonly legislated of these procedures, used internationally, are Environmental Impact Assessments (EIA) and Strategic Environmental Assessments (SEA) impacts (Bobylev, 2011). These decision-making tools both consider the environmental impact of a proposed project. However, EIA gives information about the possible environmental impact of a project and executes mitigations planning, while SEA efficiently draws up the overall policy and investigates its associated impacts (Department for Communities and Local Government, 2015).

2.5.2.2 Society

Cities that benefit from the use of underground space have acknowledged that its use is a pre-requisite for modern living and society as a whole (Hanamura, 1988). For instance, in developed cities, UUS is mostly dedicated to public services that are required, but also now expected by society, these include transport links, shopping centres (and associated car parking spaces), doctors operating surgeries, cinemas, and theatres (Hanamura, 1988). Its private use is limited to car garages and storage (e.g. basements). UUS is perceived as a good way of providing transportation alternatives such as railways, roads etc.

Air quality is one of the essential considerations for a society. A recent research study has shown that air pollution is likely to reduce human life expectancy in the UK by an average of 6 months and in other developing countries by much more (Defra, 2010). Underground transportation routes could provide a solution for reducing pollution in dense cities. However, underground facilities may also have negative impacts on society. For instance, psychological aspects can affect people's comfort either by draft and air-flux (caused by passing metro) or through noise and vibration of underground trains in shallow tunnels, although the latter will decrease quickly with depth and distance from source (Sterling and Godard, 2000; Bobylev, 2009). In addition, Bobylev (2009) recognises the major problems associated with long underground pedestrian routes, not least their attractiveness to criminals. Closed-circuit television (CCTV) can help in this respect, although cameras need to be in the right location and permanently manned, this brings with it another economic cost.

2.5.2.3 Economy

Despite the obvious advancement in technology and construction methods (for example Multi -utility tunnels (MUT) which eliminates the need for frequent excavation and reinstatement) (Curiel-Esparzaa and Canto-Perello, 2012; Hunt et al., 2014), underground developments are often considered to incur higher initial costs than developments located on the surface (Maire et al., 2006; Curiel-Esparzaa and Canto-Perello, 2012; Hunt et al., 2014). For example, traditionally, underground construction has been done using open-cut method. This method is expensive and also additional costs are usually incurred through, for example, disruption to the traffic or adverse impact on nearby businesses (Allouche et al., 2000). This issue can give rise to doubts relating to the effectiveness of investing necessary public funds (ITA, 1985). An estimation given by Zhao and Cao (2011) suggests a ratio increase of two to four times for UUS construction compared with above ground, which is a significant drawback. However, particular arrangements including geological specification scale and structure type may deliver direct and in-direct benefits in terms of construction costs. For example, the Crossrail programme is estimated to bring £42bn to the economy of the UK, which offsets the huge costs of UUS construction (Crossrail, 2017).

This section has reviewed the underground space, its relationship with sustainability and different ways it can impact sustainability. The following section (Section 2.6) reviews the current tools and evaluation frameworks pertaining to sustainability. The review includes the most common tools/framework, which are deemed the most appropriate to sustainable development.

2.6 Sustainability Evaluation Tools in Geotechnical Engineering (UUS)

The previous sections have discussed the growth of world population and lack of space, highlighting the essential role of UUS in overcoming the cities challenges, which has ultimately resulted in the suggestion of underground space development as an effective solution for sustainable developments. This section aims to review the current sustainability assessment tools to select the most appropriate tools for UUS assessment, and ultimately develop a holistic assessment tool.

Sustainability assessments must first answer two questions before selecting the suitable tool.

- First determining what should be measured. This could be partially answered by understanding the origins, fundamentals and principles of sustainability.
- Second, determining how to measure the set of criteria. Measurements in this respect can range from objective and quantitative to more subjective or qualitative metrics. (Poveda and Young, 2015).

To answer the first question with respect to UUS, it is necessary to consider that 'space' is only one of four resources that conceptually make up the subsurface, the others are water, geo-energy and geomaterials. The use of UUS for any goals and purposes has to consider the existence of these four resources, and how they can influence each other (Parriaux et al., 2006; Parriaux et al., 2008; Bobylev, 2009; Admiraal and Cornaro, 2016b). Also, authors, such as Li (2013a, b), highlight that underground urbanisation focuses on the development of underground space, however, sustainable underground urbanisation has to include all four resources, including, space, water, energy and geomaterial.

As a result, it becomes complicated, for example, when a city has invested in energy applications but then realises this is in conflict with the extraction of drinking water due to the pollution of natural aquifers. Therefore, for UUS assessment there is an absolute need to identify and consider the fact that the four used resources could easily conflict (Admiraal and Cornaro, 2016b).

With respect to the second question, the sustainability concept within this research has been considered to be based on the three-pillar approach method (explained in Section 2.5) and based on four resources of underground. Bobylev (2016) and Song et al., (2013) suggest a traditional method of listing indicators under the three-pillars of sustainability (i.e. environment, society and economic) to develop a holistic tool including relevant indicators for underground space. Hence, existing tools are reviewed to find a tool, taking into consideration a balance between three pillars of sustainability, and including indicators relevant to the four resources of UUS.

As a result of this process, in order to review the current tools, three main categories of sustainability assessment tools were selected for detailed investigation. The first category includes tools that are award-based, meaning that the tool will demonstrate the performance of the project with a specifically designed format. These include the Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED) for buildings; and Civil Engineering Environmental Quality Assessment and Award Scheme (CEEQUAL) which is applicable to all infrastructures. The second group are continual improvement tools, which are not award-based, and could be applied at different stages of the project to track the performance progress within a graph. The graph aims to show weaknesses of the project in order to help the stakeholder get to the ultimate goal of sustainability. This group includes tools such as Horizon, the Halcrow Sustainability Toolkit and Rating System (HalSTAR) and Sustainable Project Appraisal Routine (SPeAR®), for use in all civil infrastructure projects. These tools are described by Venables et al., (2005), Poston et al., (2010), Pearce et al., (2012) and Clevenger et al., (2013). Other recently developed sustainability assessment systems for use in the UUS industry, specifically in different countries around the world have been developed by Koo et al., (2009), Fu (2012), Song et al., (2013), Li et al., (2012) (the deep city model), Xiaoxiao (2014) and Bobylev (2016). However, they are presented in a set of indicator sets that pertain to UUS, rather than an assessment method.

Table 2.1 presents a summary list of these sustainability assessment methods, in terms of their application and assessment methodology, in addition to the key aspects of each system and their potential impact when used in the context of UUS. Each indicator system is reviewed in detail in Sections 2.6.1 and 2.6.2.

Table 2.1:List of sustainability indicator systems

		Name / developer	Building or Underground	Assessment criteria		Weighting	Results format
Civil engineering assessment tools	Award-based tools	**LEED**	Environmental assessment method with building focus	-Sustainable sites -Water efficiency -Regional priority -Indoor environmental -Quality -Innovation -Design process	-Energy and atmosphere -Materials and resources	Weighted	-Certified -Silver -Gold -Platinum
		BREEAM		-Management -Health & Wellbeing -Energy -Transport -Water	-Materials -Waste -Land Use & Ecology -Pollution -Innovation (additional)	Weighted	-Pass -Good -Very Good -Excellent -Outstanding
		CEEQUAL	Environmental assessment tool of all infrastructures	-Project Strategy -Client Contract Strategy -Project or Contract Management -People and Communities -Land use and Landscape	-Ecology and Biodiversity -Water Environment (fresh & marine) -Physical Resources Use and Management -Transport -The Historic Environment	Weighted	-Pass -Good -Very Good -Excellent
	Continual improvement tools	**Horizon**	Sustainable economy focused	-Environmental -Social and political foundations -Essential needs		Prioritisation with a series of cards	Circular graph presentation
		HalSTAR	Generic sustainability	Wide range of indicators and sub-indicators		Can involve assigning of weightings and	Circular graph

		assessment tool with stakeholder focused management		employment of multi-criteria analysis	presentation
	SPeAR®	Generic sustainability tool	120 indicators of: -Social -Economic -Environmental	No weighting	Circular graph presentation
	Underground specific indicators				
Indicator sets	**Fu (2012)**	UUS assessment	-Site & underground space planning -Structure design -Construction & resource conservation -Operation and maintenance -Retrofit and upgrade	No weighting	-
	Koo et al., (2009)		-Construction Material Selection -Construction Method Selection -Pollution -Land and space use -Project management -Community and public -Owner's issues -Security issues	AHP/Pairwise comparison	-
	Song et al., (2013)		22 indicators -Environment -Society -Economic	AHP	Graph representation
	Deep city model		-Subsurface geotechnical quality -Groundwater quality -Geothermal energy -Geo-materials quality -Urban population -Living density -GDP per capita	Weighted	Graph representation
	Bobylev (2015)		-Developed UUS volume (m^3) -Developed UUS volume per person (m^3/person)	No weighting	-

				-UUS use density (m3/m2)		
		Xiaoxiao (2014)		-Economic -Social -Environmental -Planning and design part	No weighting	-

2.6.1 Award-based tools

There are a range of well-established sustainable indicator systems that can be used to assess a whole range of issues related to sustainable development at international levels, e.g. United Nations (UN) indicators, national levels, e.g. the UK Government's headline indicators and local levels (Hunt et al., 2008). Unfortunately, these are very generic considerations and do not explicitly mention UUS. Most commonly used indicator systems are described below.

2.6.1.1 LEED

Leadership in Energy and Environmental Design (LEED) framework system was developed in 1996 by the U.S. Green Building Council (USGBC). It is an award-based tool which certifies buildings as silver, gold or platinum. It aims to evaluate building's performance through seven major categories:

- Sustainable Site
- Water Efficiency
- Energy and Atmosphere
- Materials and Resources
- Indoor Environment Quality
- Innovation and Design Process
- Regional Priority Credits (Ding, 2008; Poveda and Lipsett, 2011; Sullivan, 2014; Wu et al., 2016).

LEED system evaluates the environmental performance of buildings from an overall point of view during their lifecycle (Asdrubali et al., 2015). However, it is evident that the LEED categories emphasise only environmental aspects of a building's performance namely water, energy and materials. Another significant aspect is that the LEED system is heavily weighted to encourage energy-efficient building performance which will significantly affect final performance values and, hence, certification (Wu et al., 2016).

Even so, Tsai and Chang (2012) discuss that there is a room for improvements in the guidance documents in order to identify more appropriate indicator items and associated measures to facilitate sustainable design.

Due to its building focused nature, there is no inclusion of underground space assessment and therefore LEED fails to be an appropriate choice for the purpose of UUS assessment (Green Building, 2013). Whilst it could be argued that can be used to assess a building, parts of which may be located below ground, it does not of its own fulfil the remit of a generic UUS assessment tool.

2.6.1.2 BREEAM

The Building Research Establishment Environmental Assessment Method (BREEAM) was developed by the Building Research Establishment (BRE) in the UK in 1991. BREEAM is an award-based tool and has been well received and well used within the UK (Hunt et al., 2008; Hunt et al., 2009). It assesses the level of environmental performance for a building in addition to broader aspects of sustainability (Bre, 2016; Asdrubali et al., 2015).

BREEAM contains nine different categories, and it uses a fixed weighting system to provide a means of defining, and ranking the relative impact of environmental issues. The assessment is undertaken in terms of following categories:

- Management;
- Health and Wellbeing;
- Energy;
- Transport;
- Water;
- Materials;
- Waste;
- Land Use and Ecology;
- Pollution;
- And Innovation (additional) (Bre, 2016).

The overall indicator credit score will be awarded as either: Pass, Good, Very Good Excellent or Outstanding (Bre, 2016; Roderick et al., 2009).

Whilst BRE has developed indicators specific to utilities these do not feature in BREEAM Moreover, whilst utilities are undoubtedly located below ground and do impact sustainability, the system does not currently deal with any of the broader aspects of UUS. As with LEED, it is related more to buildings, with a focus on environmental performance. This is an opinion shared by Campbell-Lendrum and Ferris (2008), Hurley et al., (2008) and Hunt et al., (2007, 2008).

2.6.1.3 CEEQUAL

The Civil Engineering Environmental Quality Assessment and Awards scheme (CEEQUAL) was developed in 2003 and is promoted by the Institution of Civil Engineers (ICE)

(CEEQUAL, 2016). It is an assessment and awards scheme aimed at enhancing sustainability in areas of civil engineering, landscaping and public realm. It is intended to work along with statutory frameworks during different stages of the project timeline i.e. through construction, operation and finally to completion (Phillips, 2016; CEEQUAL, 2016). A project is scored using 9 areas that cover a range of environmental and social issues: These nine areas are (CEEQUAL, 2016):

- Project/contract strategy
- Project/ contract management
- People and communities
- Land use (above and below water) and Landscape
- The Historic Environment
- Ecology and Biodiversity
- Water Environment (fresh & marine)
- Physical Resources Use and Management
- Transport.

Once the assessment is done, the project team or contract team is granted an award based on the percentage score achieved (100 being the highest possible score). The CEEQUAL award certificate, which is a representation of the level of achievement is in the form of Pass, Good, Very Good or Excellent, scale (CEEQUAL, 2016).

CEEQUAL, is applicable to many civil engineering projects including UUS, however, given its predominately-environmental focus, it fails to provide the required holistic coverage to fully assess sustainability of UUS. In order to make it a holistic approach, more UUS specific indictors would need to be added to provide a balance between the three pillars of sustainability (Holt et al., 2010a). Another drawback discussed by Hayes et al., (2012) is that since it aims to cover different civil engineering projects, it generally results in a large number of criteria, which in turn makes using this tool a time-consuming process.

This section has reviewed the tools LEED, BREEAM and CEEQUAL. The first two are building related and the latter is applicable to all infrastructures. However, all three tools lack a balanced holistic approach (there is an emphasis on environmental considerations), which makes it undesirable for UUS. Importantly, they have been criticised for their awarding focus, which does not truly encourage different stakeholders involved in a project to improve sustainability, but to treat such assessment solely as a checklist to tick as many boxes as possible to achieve the award.

2.6.2 Continual improvement tools

This section will review tools that are not award driven, but continual improvement, such as Horizon, HalsTar and SPeAR®, described below.

2.6.2.1 Horizon

A number of frameworks have been developed by individuals and groups. An example is Horizon (Figure 2.11) which has been developed by the Forum for the Future, the Technology Strategy Board and Aviva Investors. This Sustainable Economy Framework (SEF) defines a safe environment with social benefits under a sustainable economy (Horizon, 2012).

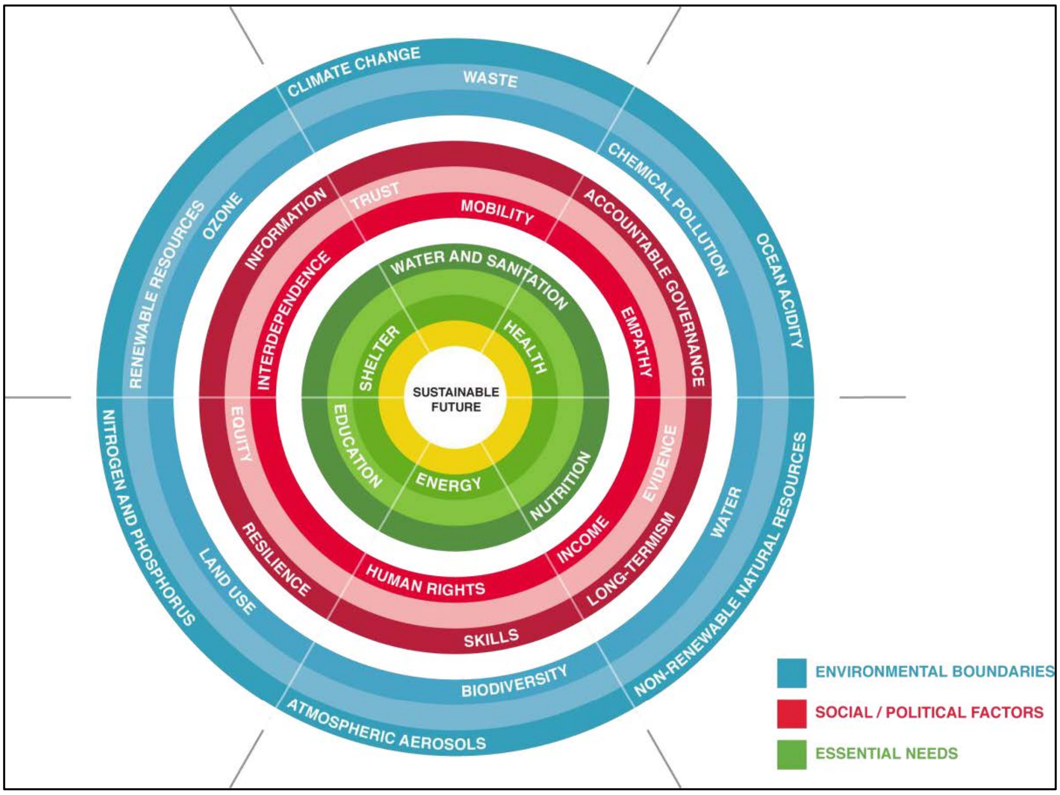


Figure 2.11: A snapshot of Horizon tool (Horizon, 2012)

It has been presented in a circular graph, consisting of three layers: the outer one is the environment, the middle one indicates social and political foundations and essential needs to thrive in the inner ring, lastly the core is a sustainable future (Figure 2.11) (Horizon, 2012). Hence, although the ultimate sustainability is the goal, it is based on the three pillars of environment, social and essential needs, which differ from those set out in this research as three pillars of sustainability (i.e. environment, society and economic).

Horizon represents each of the categories as a series of cards. There is an option on each card, providing an overview of the issue and the reason behind that and presents some suggestions as to how and when to take risks and create opportunities. Overall, it helps an organisation evaluate the actions that it should or could take (Horizon, 2012). However, this does not provide a comprehensive approach for UUS assessment.

2.6.2.2 HalSTAR

(HalSTAR) (Pearce et al., 2012). It is designed as a diagram to assess and manage sustainability and represents a balance between a range of needs, for a nested system of stakeholders throughout a project (Figure 2.12). The HalSTAR process considers stakeholder priorities whether those of government, local authorities, investors or end users. At present, the resultant database of generic sustainability requirements contains approximately 840 sub issues, with approximately 4200 qualitative criteria and 2000 different indicators identified (Pearce et al., 2012). Even though it covers a range of indicators, authors, such as Holt et al., (2010a), have criticised it as being over complicated and time consuming to use and, therefore, unsuitable for use in a specific project with specific requirements. This has been named ‘tool fatigue’ by Holt et al., (2010a) which could be the case for the development of a new assessment method. Furthermore, being a stakeholder focused management tool, considering a stakeholder’s priorities, as well as including a wide range of indicators, make it unsuitable for this research

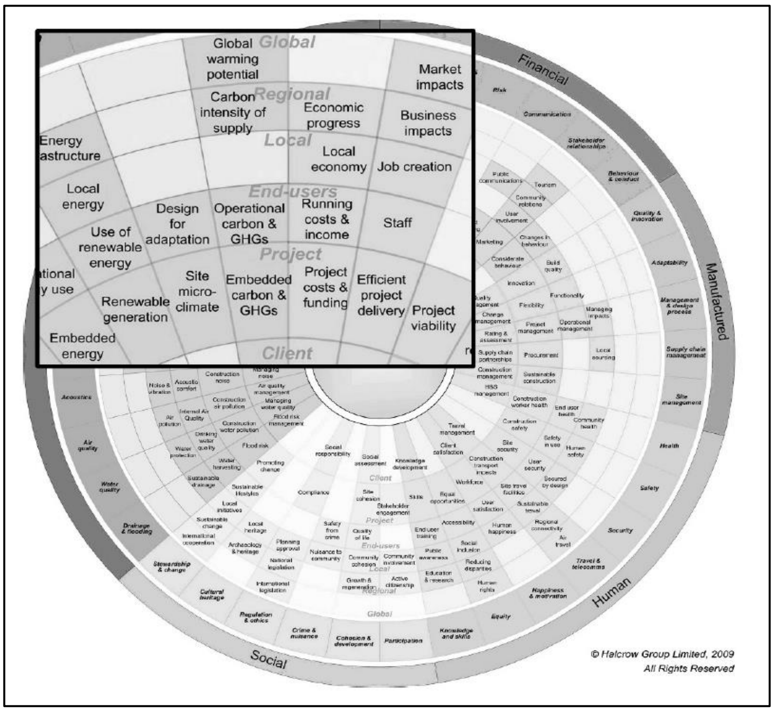


Figure 2.12: A snapshot of HalSTAR tool (Pearce et al., 2012)

2.6.2.3 SPeAR®

The Sustainable Project Appraisal Routine (SPeAR®) framework, established by Ove Arup and Partners Ltd. in 2001 (Figure 2.13) (Braithwaite, 2007; Arup, 2015a). SPeAR® contains a set of core indicators and sub-indicators that has been widely reviewed by a range of professions. The main purpose behind its development was to incorporate a broad range of sustainability issues, which would cover most built environment projects. The system evaluates sustainability performance measures, using a three-quadrant model that focuses on the key elements of environmental, social and economic (Arup, 2012). SPeAR® is supported by a series of detailed worksheets, with over 120 sub-indicators of social, economic and environmental performance (Braithwaite, 2007; Holt et al., 2010a). The assessment is based on the performance of each indicator against a scale of best and worst cases (Holt et al., 2010b).

There is a diagram, which shows the performance of groups of indicators by shading in a segment of the face. The closer that segment is to the centre of the diagram; the stronger it is in terms of sustainability, conversely, the further away it is from the centre, the weaker the segment. Braithwaite (2007) compares the diagram with a dartboard, and describes the main aim as being a requirement to have as many as segments possible close to the centre. Information shown on the diagram is a direct reflection of the availability and quality of information available at the time of data collection, which is used to complete the worksheets. However certain projects will need indicators to be modified or new indicator sets to be developed as a part of the tool (Arup, 2012). Its difference with HalSTAR is that SPeAR® only includes 120 indicators, compared to the 2000 indicators identified within HalSTAR, hence, it is not prone to tool fatigue. In addition to this, there is no focus on stakeholder prioritisation, which means it incorporates a generic overview. Compared with other tools, such as LEED, BREAM and CEEQUAL, SPeAR® is not award-based, which are known to be prone to an in-built bias (Holt et al., 2010a), and it does not include weighting for the indicators or criteria (Braithwaite, 2007; Holt et al., 2012a). It is used as a continual improvement tool and could be applied to different stages of a project from design to maintenance, and to monitor performance. SPeAR® aims to show the state of the project, helping and encouraging the stakeholders to make improvements. However, Holt et al., (2012a) criticised this tool for over simplification by providing a generic overview and limiting the list of indicators.

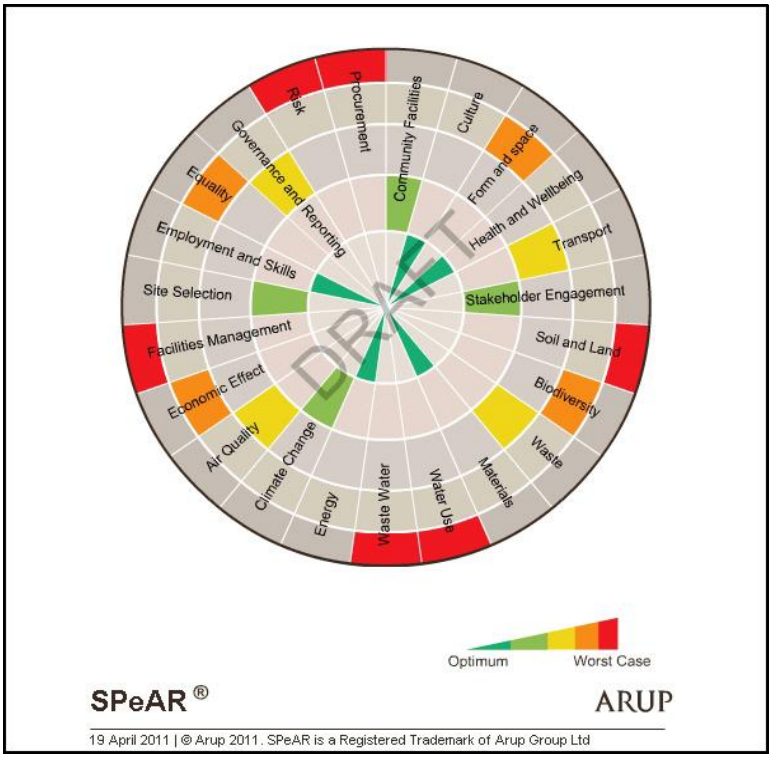


Figure 2.13: A snapshot of SPeAR® tool (Arup, 2012)

2.6.3 Underground specific indicators

A number of authors have developed UUS specific indicators that relate to individual aspects of UUS and therefore individually they do not constitute a holistic sustainability assessment tool for UUS. These are neither award-based tools nor continual improvement. These are mainly demonstrated in a series of indicators with respect to UUS. These are previously described in Table 2.1, a discussion on the reason these not being a comprehensive assessment is provided below.

- Fu (2012) discusses a number of major issues, which have to be considered with regards to the five categories given in the Table 2.1 however it does not constitute a specific set of indicators or a framework that can be adopted for sustainable use of

UUS. The framework has been presented as a generic guidance and it is not clear how to apply this to UUS.

- Koo et al., (2009) developed a tool called The Sustainability Assessment Model (SAM) Based on triple bottom sustainability model. The tool includes forty-seven sustainability indicators contained therein represent sustainability issues highlighted under 8 major categories (Table 2.1). The authors have suggested a series of methods for the assessment of the sustainability indicators that include: 1) Analytic Hierarchy Process (AHP); 2) real cost estimation; 3) pollution estimation; 4) energy estimation; 5) time estimation; and 6) natural resource depletion impact analysis.

Even though the authors introduce a series of indicators relevant to underground infrastructures, as well as some methods to be able to measure them, a certain number of indicators essential to underground space assessment, such as water (one of the resources associated with underground space), are missing. Also, assessment methods are only superficially introduced, without describing the required details. Therefore, further refinement to SAM would likely be required. Furthermore, no specific methodology for the tool implementation has been provided and it is not evident how the output could be obtained.

- Song et al., (2013) developed a set of indicator systems for UUS use based on OECD, PCSD, EU, and Ministry of Environment indicators. The shortfall of the system is that it only includes 22 indicators (Figure 2.14) but there is no sub-indicators. Therefore, it will provide only an overall look into sustainability, which is useful, although without sufficient details would not allow more informed city decisions with respect to UUS to be made.

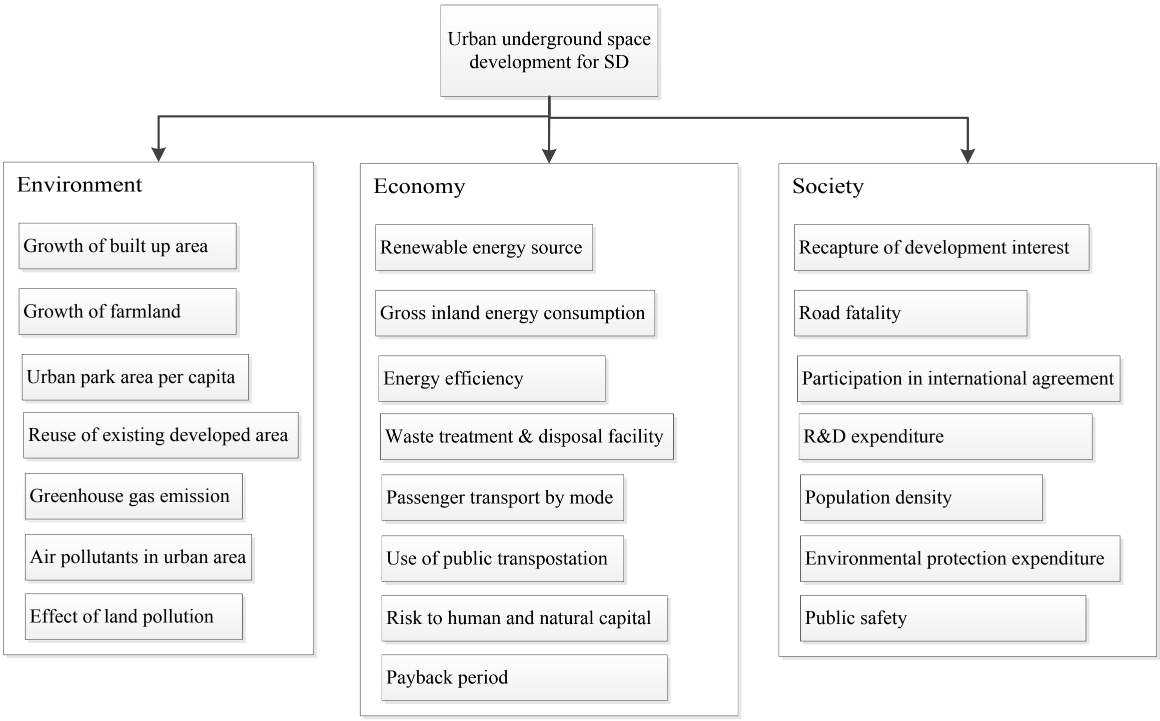


Figure 2.14: Indicators related to UUS considered by Song et al., (2013)

- Li et al., (2012) and Li et al., (2013a, b) have proposed a UUS approach named ''The Deep City Method''. The method is aimed at helping decision-makers to exploit the full potential of UUS into city-scale planning as well as urban underground asset management. Within this methodology, there is consideration for the availability of many UUS resources including groundwater, geo-materials and geothermal energy. The method involves a number of steps to incorporate UUS more fully into the planning process. However, the research focuses on economic and institutional feasibility of underground space development with respect to the four identified resources of underground space, highlighting that the underground will become a strategic resource for urban growth. Therefore, the authors attempt to introduce a new management process for strategic thinking and operational planning practices, combining understandings on supply and demand schemes of underground resources. These researchers looked at the possibilities of going underground in order to release the pressure on space above ground. For example, following criteria with the relative weightings have been introduced within this research to identify a particular city which deserves an imminent management of the urban underground.

- Subsurface geotechnical quality
- Groundwater quality
- Geothermal energy
- Geomaterial quality
- Urban population
- Living density
- GDP per capita

Unfortunately, the approach acts more in favour of a management strategy rather than an assessment tool. Specific indicator sets are missing and therefore there is not possibility of assessing the sustainability performance of UUS. Therefore, although it is a good guideline for UUS consideration in urban planning it cannot be used as a toolkit for sustainability assessment therein (Li et al., 2012; Li et al., 2013a, b).

- Bobylev (2016) has reviewed current sustainability indicator systems and emphasised the importance of including UUS in indicator lists in order to achieve an integrated and comprehensive sustainability assessment. However, the author does not provide an assessment tool or framework and his methodology is limited due to its restriction to three elements (Table 2.1) which are considered the best way to consider UUS in urban agendas. This approach therefore has limitations.

- Xiaoxiao (2014) has considered the concept of urban sustainability in his developed framework, which is divided into four subsystems: environmental, social, economic and design aspects. Indicators in this study were collected through interview with designers, planners, governmental officials, and onsite observation. However, within this methodology it can be seen that the indicators are designed specifically with respect to Hong Kong's environment (i.e. local context and conditions) and therefore cannot be utilised as general indicators for underground space assessment. Moreover, the outcome of the study is only a list of generalized indicators without any accompanying weighting and it is unclear as to how those can be used for further assessment of underground space.

Each of the developed assessment tools reviewed utilises its own particular weightings and calculation system (Sharifi and Murayama, 2013). Normally, as the tools have been intended to cover a range of issues; they give benchmarking and priority levels for the selected criteria, and they depend on different databases, rules and questionnaires (AlWaer and Kirk, 2012). Since the different assessment approaches, models, appraisals, instruments, processes, strategies, and methodologies have demonstrated their usefulness throughout the years (Yudelson, 2008; Mateus and Braganca, 2011; Reed et al., 2011; Conte and Monno, 2012), scientists and practitioners must be encouraged to continuing developing, adapting improving and implementing these tools.

Reviewing existing tools has demonstrated that no single tool proved suitable for a sustainability assessment of UUS. The review showed that tools such as LEED, BREEAM are building related and their focus is on environmental aspects. CEEQUAL is applicable to all projects, however it is criticised for being award driven and also prone to tool fatigue. Similarly, the continual improvement tools, such as Horizon and HalSTAR, include a large number of indicators and have been criticised for tool fatigue and for being over complicated. Other tools which have been specifically designed for UUS have been reviewed, for which it was not evident how to use their tool, and that they mainly consist of generic guide lines. However, SPeAR®, which includes 120 indicators and is not award-based, has been considered as a potential shortlisted tool/method that could be used to develop a novel, holistic assessment framework for UUS. It is a continual improvement tool which allows the user to monitor the progress of the project. It has been criticised for being over simplified, but it is ideal for this research, as it would allow for necessary modification in order to use it for the development of a new tool. More justification of using SPeAR® in this research is given in Chapter 4.

Providing the comparison between the existing sustainability assessment tools, the next section (Section 2.6.4) compares the differences between a tool designed for improving sustainability of underground construction or comparing between above or underground alternative.

2.6.4 Distinction between a tool for improving sustainability of underground construction or comparing between above or underground

In Sections 2.6.1 to 2.6.3 a series of tools have been reviewed which could be used for UUS, such as LEED, BREEAM, CEEQUAL or HalSTAR in the award-based category, and tools such as SPeAR® and HalSTAR in the continual improvement category. The review showed that, apart from LEED and BREEAM, which are specifically designed for buildings, all other tools are designed to be applied to all infrastructures, including UUS and above ground. However, there might be potential issues when utilising these tools for assessing a UUS project. For instance, CEEQUAL could be applied to all infrastructures projects and could be used to assess a project to make a decision to whether to go underground or to stay above the ground. However, to be applicable to both above and below ground, it includes a large number of indicators to cover both options, which makes it time consuming to use when only underground assessment is required, and hence, it attracts criticism for over complication and tool fatigue. This is also the case for HalSTAR as, although it includes many indicators covering both underground and above ground, in reality, a large number of indicators are not desirable and it makes the assessment difficult and time consuming. Allied to this, when above ground is concerned, environmental aspects become more severe, as it is evident in tools such as LEED and BREAAM, which focus more on environmental aspects.

Fu (2012) and Song et al., (2013) have previously introduced few specific indicators for UUS, but those do not cover all aspects of sustainability. Hence, for this research to be able to develop a tool with a balanced consideration of the three pillars of sustainability and to address the need for a tool assessing the impact of UUS, it is considered necessary to develop a tool specifically for a project which is destined to go underground.

2.7 The Need for a Weighting System

Sustainability is a complex concept that can be measured in a variety of aspects, e.g. the three-pillar approach (Cole, 1998; Cooper, 1999; Crawley and Aho, 1999; Wong and Abe, 2014). Designing a weighting system is one of the most common and viable methods for prioritising these aspects (Chang et al., 2007). Hence, a reliable weighting system is required to acknowledge and institutionalise the importance of these aspects and criteria (Lee et al., 2002; Cole 2005). Furthermore, it has been reported that the development of a weighting system of sustainability criteria is the key to any successful assessment method (Chang et al., 2007; Alyami and Rezgui, 2012).

According to Poveda and Young (2015), to accomplish an improvement in sustainability performance, the building industry has utilised weighting system as guidelines in order to evolve and implement its vision of sustainability and technological innovation. Nonetheless, sustainability is rapidly changing in an urban context, therefore the building industry must adopt assessment tools that can be adjusted in order to meet the emerging needs of a range of stakeholders. Such advancement has come about either in the form of assessment practices (with the point of benchmarking performance) or adjustment of existing tools and/or improvement of new ones to meet particular visions of sustainability. The authors outline that the weighting system typically consists of a series of criteria collected in areas of relevance (i.e. categories) for easy identification and management. Additionally, the developer of these rating systems then designs a weighting system that assigns each criterion with a respective weight.

According to Sullivan et al., (2014), there are very few pieces of research that investigate the reasons for adopting weightings within sustainability frameworks (and the differences between them), though some papers propose hypothetical explanations. For instance, the difference in weightings between LEED and BREEAM goes back to the principles they are based on. LEED looks into 'new urbanism' highlighting site selection and connectivity, while BREEAM tends to consider more 'environmental concerns' (Kyrkou and Karthaus, 2011). The weightings in the latter stem from environmental profiling methods with weightings being based on the result of stakeholder engagement and consensus.

A weighting system can be utilised to differentiate the importance of individual or multiple indicators over others within a decision-making process. Weights represent the importance of each decision/criterion relative to all others (Pulipati and Mattingly, 2013). Weighting is one of the most theoretically controversial aspects within the sustainability assessment tools (Alwaer et al., 2008; Retzlaff, 2009). It implies the significance and importance of different criteria, although it is extremely difficult to compare and rank different elements (Retzlaff, 2009). The often subjective nature of scoring and weighting different criteria (Vakili-Ardebili and Boussabaine, 2007; Garde, 2009; Retzlaff, 2009), has made this practice vulnerable to ambiguity (Kajikawa et al., 2011).

A key feature of weighting systems is their emphasis on the decision-makers' judgements for estimating weights. This judgment affects the contribution of each indicator, and/or sub-indicator, on overall assessment. Authors, such as Kao (2010) and Lotfi et al., (2013), point out other benefits of utilising weighting, for instance since the process shows the emphases of the decision maker, it serves as a guide for future development. For example, if a higher weight is assigned to pollution compared to the weight of profit, then more effort will be devoted to control the pollution than to profit generation to obtain a better performance (i.e. higher rank).

The source of underlying values of the weighting may be 1) expert opinion, e.g. by panel method, 2) political directives, and 3) members of the public. The weighting can be achieved in two ways: subjectively and objectively. The former includes determining the weight by subjective judgments of experts or decision makers (Jiang and Shen, 2013). In other words, the weights are developed by asking a group of experts to assess how the different criteria of sustainability relate to each other. Potential shortcomings of weighting can be linked to the subjective weighting methods, when utilised, which reflect the subjective judgment of the decision maker meaning that the final weight can be influenced by the decision maker's level of knowledge and experience in the relevant field (Zardari et al., 2015). However, the weighting of indicators is an important issue when it comes to sustainability aspects, as not all indicators are equally important (Mikulic et al., 2015). However, objective data, such as historical costs, can be utilised in such a judgment to mitigate the embodied subjectivity. According to OECD (1998), weighting is strongly linked to values and it is characterised by subjective elements. Applying weighting, however, can enhance decision-making process by bringing a higher level of structure, analysis and openness that lie beyond the common decision making (Department for Communities and Local Government, 2009)

The next section (Section 2.8) will provide evidence to suggest the gap of the knowledge and novelty of this research project.

2.8 Gap of Knowledge

Literature presented in this chapter, has highlighted the issue that as the world continues to urbanise, sustainable development challenges will be increasingly concentrated in cities, hence, there would be greater use of UUS. Considering the sustainability concept and the concern that UUS is a non-renewable resource, there is an alarming fact to consider these issues more methodologically. Although there is no common agreement around some aspects of sustainability, there is certainty the need for the development and implementation of tools to measure the progress made towards its goal(s).

As discussed in Section 2.6, there is a range of well-established sustainable indicator systems/tools that can be used to assess a whole range of issues related to sustainable development, which cover an extensive array of civil engineering projects. However, they do not address the sustainability performance of a project which is destined to go underground. This is a significant shortfall for decision makers, who seek to improve the sustainability performance of an underground project. A substantial knowledge gap has been identified within the literature, which shapes the aim of this research.

The literature review has demonstrated that several attempts have been made to produce UUS specific assessment tools from a range of different authors or organisations. However, amongst the methods/tools reviewed, none of them appear to be a comprehensive tool for assessing the sustainability of UUS.

Therefore, when given the option of going underground vs over ground there are still a variety of questions to be answered such as: how would building this structure underground aid sustainability? In what ways and how? What are the weaknesses? And, if so how can we improve it? When considering these questions in combination, this places a great demand on development of a new decision-making framework system such as that proposed and developed within this thesis.

2.8.1 Novelty of work

Bearing in mind the gap of knowledge and the need for a sustainability assessment tool to align with the rapidly growing sustainability vision, the author aims to develop a specific UUS assessment tool that allows underground stakeholders to evaluate sustainability performance of a project which is destined to go underground. The author's contribution to the research is the development of a tool which is capable of sustainability assessment of UUS.

Development of the tool mainly consists of two phases:

- An indicator system base for UUS;
- A weighting system assigned to the selected indicators.

These two coupled together in a form of excel spreadsheet forms a graphical presentation of a tool which can be used for any UUS project. Later the tool has been tested using two case studies, one in the London- UK and another one in Tehran- Iran to show the application of the tool. Subsequently the arising impact of cost of UUS construction has been discussed and the implications of the tool with respect to cost considerations have been shown. The methodology of the tool development has been explained in the next chapter (Chapter 3) in detail.

2.9 Summary

This chapter has reviewed literature associated with:

- UUS and its different aspects
- Sustainability concept and its relationship with underground space utilisation
- Current sustainability indicator systems / tools

The literature review presented in this chapter highlighted the importance of underground space use in our urban environment. The history of underground space use has been reviewed and critical review of underground infrastructures divided to two categories of functional infrastructures and passing and living spaces have been undertaken. Accordingly, benefits and drawbacks of underground facilities have been presented.

The sustainability concept, also, has been studied which ultimately leads to the relationship it could possibly have with UUS use. It has been found out that there is a need for greater well-planned UUS use in urban environments, and the role that UUS has in our sustainable future cities is significant. Ultimately, in order to measure the contribution of underground space use to sustainability, a range of sustainability assessment tools have been reviewed.

Through the review of the literature, the tools developed by other researchers or companies were scrutinised. It has been identified that there are sustainability assessment tools (such as BREEAM, CEEQUAL and SPeAR®) which cover a range of sustainability issues. However, they lack the inclusion of UUS specifically. Therefore, the author emphasises that a specific tool designed for UUS that holistically represents the impact(s) on sustainability has yet to be developed.

CHAPTER 3: METHODOLOGY

The review of the literature on UUS and sustainability demonstrated that there has been little research undertaken to aid the development of a robust framework to assess the contribution of UUS towards sustainability. To address this shortfall, this chapter presents the research methodology developed to establish a new theoretical framework to improve sustainability aspects of an underground project. The chapter consists of three discrete parts:

(1) Research Methodology (Section 3.1); which describes the methodology used to conduct the research;

(2) Theoretical Framework (Section 3.2 and 3.3); which explains the theories and factors which must be considered together in order to assess the sustainability aspects of an underground projects;

(3) Application of the theoretical framework (Section 3.4); which describes the process used to apply the developed tool to a case study.

3.1 Research Methodology

Figure 3.1 represents the steps undertaken to achieve the overall aim of this research. In summary, the steps are as follows:

1. Literature review: To have a clear understanding of sustainable use of underground space as a part of sustainability agenda, the history of underground space use and critical uses of underground space were reviewed in the literature. This included a definition of sustainable development and further investigated the relationship between the underground space and sustainability.

2. Development of a sustainability assessment tool: this included; identifying the most appropriate sustainability tool (i.e. SPeAR®) within the literature to meet the requirement of the research and the required indicators to reflect the objectives of the research.

3. Development of a weighting system: An online questionnaire was utilised to obtain the measures necessary for the weightings, and consisted of a series of qualitative questions to which respondents provide their evaluation with respect to each of the identified indicators. In order to set context, the questionnaire was accompanied by a recent UUS example; the new Library of Birmingham, Europe's largest library and one that has been used for multiple purposes.

4. Demonstration and application of the tool: In order to demonstrate the application of the developed tool, two case study assessments were carried out: Farringdon Station in London-UK and Metro Tehran line Aghdasiyeh Station in Tehran-Iran.

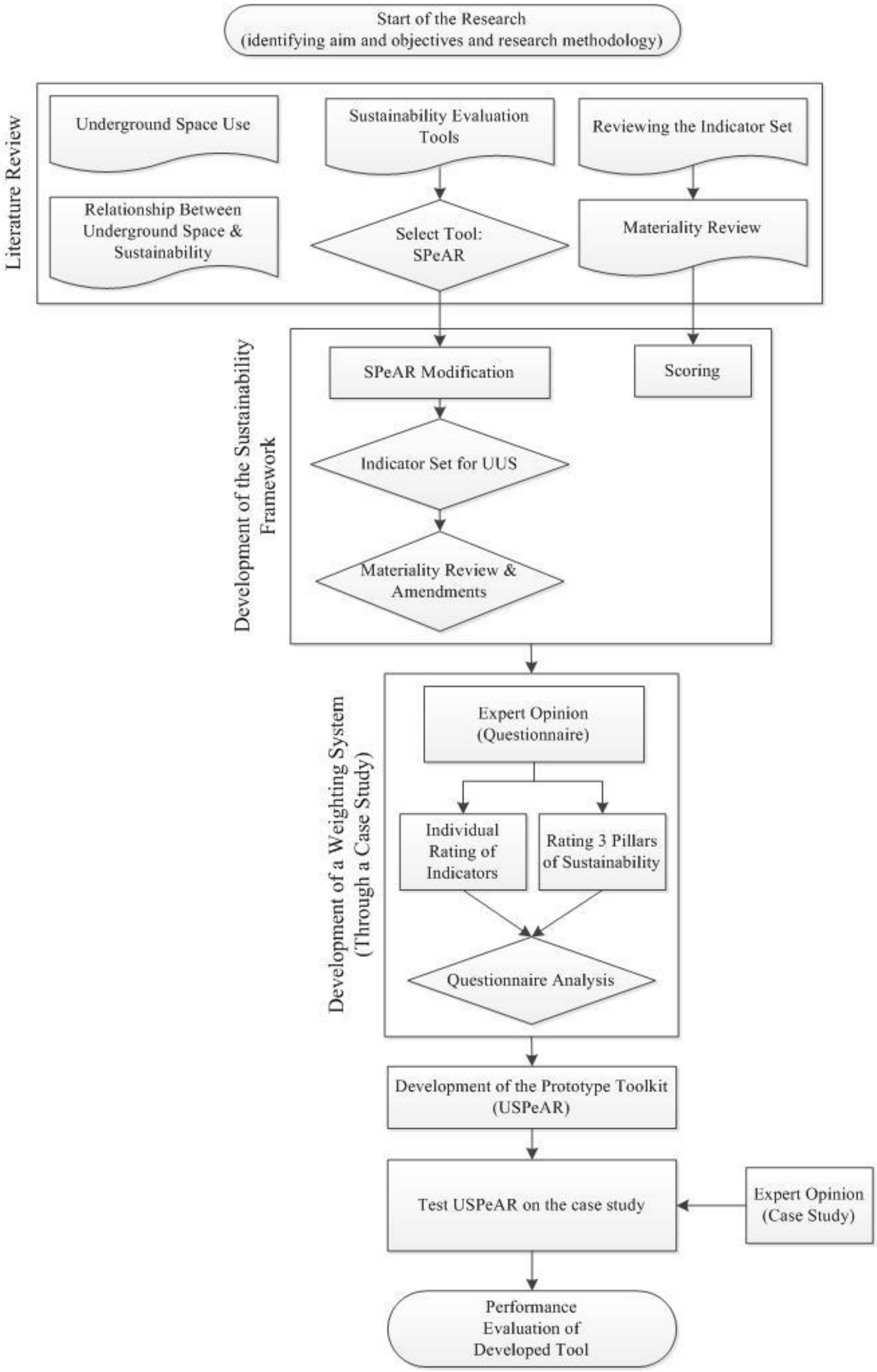


Figure 3.1: Research methodology

3.2 Development of a Sustainability Assessment Tool

Within this section step-by-step methodology undertaken in this research to develop a specific UUS assessment tool have been explained.

3.2.1 Indicator selection

The literature review chapter sums up by reviewing current sustainability indicator systems. After reviewing the current sustainability assessment tools such as LEED and BREEAM, and even specific tools designed for underground space, SPeAR® was selected as the most appropriate one to be used as a base tool and to be modified and specifically designed for underground space. In the SPeAR® tool, indicators have been provided under the three pillars of sustainability. According to SPeAR®, indicators can be removed or modified based on a 'materiality review'. However, SPeAR® does not allow inclusion of indicators other than the ones included, and there is no procedure introduced for including an indicator from other tools. So, the author only uses materiality review for the indicators within SPeAR®.

A materiality review is defined by SPeAR® as making modification to indicators based on:

- Risk
- Legal/regulatory/internal and external policy drivers
- Stakeholder concerns and societal trends
- Opportunity for innovation, and
- Best practice/peer-based norms.

It has been stated that any modification should be done by sustainability professionals. Therefore, a materiality review has been undertaken. In order to do these 25 meetings (more than 25 hours) with Mr Peter Braithwaite (Head of Sustainability and Resilience at the University of Birmingham and former member of Arup involved in the creation of SPeAR®), during 2014-15 have been held. A qualitative materiality review in the form of yes / no answers with respect to above elements has been undertaken (Appendix A). The outcome of this step is a set of indicators, which is part of the final tool, named USPeAR. The modified indicator system consists of three pillars of sustainability – environment, society and economy – with 8, 6 and 7 core indicators respectively. Allied to these are 30, 28 and 30 sub-indicators under each pillar respectively. The new tool now comprised a set of indicators and scoring system, which the latter is given by SPeAR® originally. However, in order to have a clear view of the current condition of a project, weighting must now be added to the framework.

3.2.2 Development of a weighting system for the criteria

Within the original SPeAR® tool, there are only scores, which are assigned by users. No weighting feature is provided, and therefore this gives equal priorities to each criterion. Therefore, in this research, subjective approaches will be used and a weighting will be developed for USPeAR. The developed tool would benefit from a set of weightings, which are not project specific, but general. However, a set of score exist in the tool similar to SPeAR®, which allows the user to select a score depending on the nature and performance of the project.

The weighting plays a role to indicate the relative importance of each indicator in a quantitative manner. While there are many methods to establish a weighting system, there are two types of approaches to obtain weights that reflect an indicator's importance (Yang et al., 2009; Mikulić et al., 2015; Yu et al., 2015). One method is a data-centric (objective) method where the weight is calculated by determining the numerical value of each indicator. The objective method consists of; the principal component analysis method, the factor analysis method, the grey incidence method, the entropy value method, and the rank sum ratio method. However, in the stated methods in the objective category neither the decision makers' concerns nor the experts' experiences are considered, which is a significant drawback. Therefore, the methods in the objective category are unlikely to be suitable for weighting the indicators of underground space sustainability impact (Yang et al., 2009; Yu et al., 2015; Mikulić et al., 2015).

The other method is opinion-based (subjective). In which the decision-maker judges the relative importance of the indicators by his/her personal professional judgment. The subjective category includes Delphi, Analytic Hierarchy Process (AHP), simple rank order, ratio weighting (Mikulić et al., 2015). Expert panels and AHP are two commonly used methods in this category, where importance is attached to indicators by means of rating-, ranking- or constant-sum scales (Yang et al., 2009; Yu et al., 2015; Mikulić et al., 2015).
Therefore, in this research an opinion-based (subjective) method has been adopted, an expert panel have been set to determine the indicator weightings.

3.2.2.1 Questionnaire design

A questionnaire survey is one of the tools utilised by researchers to confirm, deny or improve on what was at that point in time accepted or known (Al-rubaee, 2012). It is empirical and a well-known method concerning the potential to characterise and detail different qualities of key issues that are of interest to or critical for some readers or associations (Chauvel and Despres, 2002). A questionnaire survey provides results that can be quantified, easily treated or analysed statistically also provides an opportunity to obtain results from a large population (Ahmed, 2002; Chauvel and Despres, 2002).

The questionnaire aims to investigate the importance of each indicator of underground space with respect to sustainability. The ultimate aim of the questionnaire survey is to help in reaching a final weighting for the indicators and successfully developing a tool specifically for UUS sustainability assessment.

Weighting development: The Library of Birmingham

In order to obtain the measures that are necessary for the weighting system, an online questionnaire was prepared (Appendix B) that includes a series of questions to which respondents provide their evaluation with respect to each of the USPeAR indicators. In order to set the context, the questionnaire is accompanied by a recent UUS example within Birmingham, UK. The example pertains to the new Library of Birmingham, which is located in the city's Centenary Square and was selected. The library is a good example of where underground space has been utilised to great effect as a means of space use, water storage, and heat abstraction from a ground source heat pump connected to the underground aquifer system (Hunt et al., 2016).

The building includes a stack of four rectangular volumes, which are staggered to create various canopies and terraces. Lastly, there is a spacious under ground floor, which is extended until the edge of the train tunnel and reaches out into Centenary Square. Natural daylighting has been provided in the library through the stepping terraces and an amphitheatre in the square (Dezeen magazine, 2013; Lomholt, 2014). Ultimately, it has achieved a

BREEAM 'Excellent'. However, it is worth mentioning that the library of Birmingham is only presented as an example and respondents are asked to feel free to consider any other case of UUS facility.

3.2.2.2 Questionnaire respondents

A group of experts in all fields of civil engineering (known due to their publications or their working experiences) was contacted and invited to participate in the questionnaire during March-April 2015. From 100 experts contacted, 25 agreed to participate in the questionnaire (details are shown in Table 3.1). The questionnaire was then prepared and sent to participants. In order to ensure the panel included experts in the field with adequate knowledge and experience, they were asked a question at the beginning of questionnaire to confirm if they have more than 10 years of experience in their field of expertise (Abdullah and Anumba, 2003). This question was designed to assure the results from the questionnaire have been obtained from experts in the industry and they are valid.

Table 3.1: Breakdown of experts consulted

Field of expertise	Number of participants
Environmental activist	2
Construction professionals – Client's representative	1
Construction professionals-Contractor	5
Construction professionals- Consultant	4
Construction material producer & manufacturer	4
Local authority, policy makers & planners	3
Academics	5
National policy makers & researchers	1

3.2.2.3 Questionnaire analysis

The results from the questionnaire were collected in May 2016. The next step was to analyse the results obtained from questionnaire using a weighted average methodology, as described in detail in Chapter 5.

3.2.2.4 Weighting validation-AHP analysis

Following the questionnaire development and obtaining the final weighting for each indicator, the next step is to use the analytical hierarchy process (AHP) to estimate a weighting for each of the indicators. This method was developed by Saaty (1980) to solve decision problems and is based on expression of preference when different alternatives are available. AHP is provoked by using relative comparisons from multiple combinations of criteria and alternatives drawing from what is known as an AHP hierarchy. Additionally, it has the ability to engage a mathematical approach of multiple subjective and unquantifiable factors into decision-making processes (Koo et al., 2009).

The AHP method involves developing questions and comparing criteria against each other. The problem with adopting AHP was that it is only applicable to a project with few indicators, as for n criteria, $(n^2-n)/2$ comparisons have to be made. Due to the large number of indicators and sub-indicators in this research, this would have equated to a very large number of comparisons, which made it impractical to adopt. In addition, there has been criticism levelled at pairwise comparison, whereby different individuals may give different ratings even when trying to consider the same strength relationship (Allouche et al., 2000). Additionally, another possible disadvantage is the difficulty to comprehend the results of AHP, as the final scores from two alternatives could be very close, for example distinguishing between 0.45 and 0.43 might lead to a false result. As Allouche et al., (2000) state, it is challenging to explore the results and comprehend to what extent one is preferred over the other one, in other words identifying the degree of confidence.

Within this research, the AHP have been elicited using authors and Mr Peter Braithwaites' judgement from literature review and past experiences. This has been done in a two hour meeting and indicators raking using AHP method have been discussed.

3.3 Theoretical Framework

Four main factors are considered in this thesis in order to assess the sustainability of an underground project as presented in Figure 3.2, they are:

1. Identification of the case study; stakeholders, goals and objectives;
2. Scoring of the indicators and providing justification for each indicator;
3. Performance assessment;
4. Cost analysis;

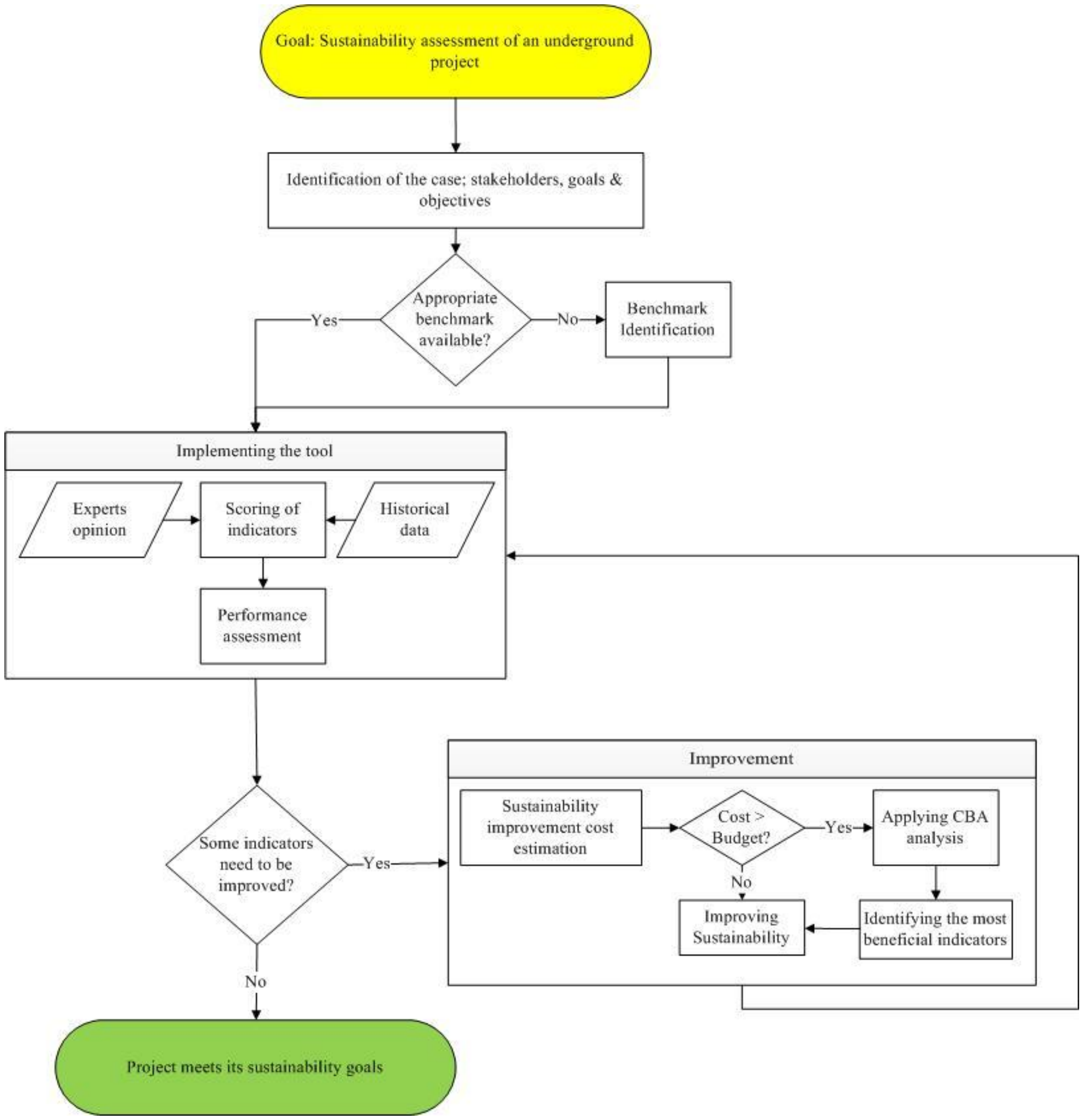


Figure 3.2: Theoretical framework

First step is to identify the overall scope of the project (i.e. the case study being considered) and its objectives, with a view of the main goal of the project. Also, to identify the key stakeholders; groups or organisations with an interest in the outcome of the project.

Step two is data collection with respect to three pillars of sustainability. Where possible, data should be referred to the project documentation or validated by third party sources. The data can be gathered from different sources, such as a literature research, review meetings or site visits, and consultations with key stakeholders. A series of guided questions provided within SPeAR® have been used for USPeAR which the performance of the project has to be assessed against. There are three main sections relating to three pillars of sustainability: environmental, social and economic. Each sub-indicator should be considered in turn and allocated a score, from -1 to 3 or worst case to exemplary, presented with colour red to green. Justification has to be provided to rationalise the score selected.

Benchmarking methods can also be used, meaning that a project with excellent performance can help to evaluate the current situation of the project in relation to the best practice (Maltz et al., 2016).

Step three undertakes the initial assessment. The output of the assessment is a radar diagram, which is a graphical representation of the scores of themes with a colour coding system. The tool highlights the final results with five colours: red is an indication of sub-standard, orange is minimum standard, yellow is good practice, light green is best practice and dark green is the most sustainable and exemplary. The procedure to this point is similar to the SPeAR® however ultimately three separate graphs of social, environmental and economic pillars within the Excel sheet present the final results in details with the weightings and colour coding.

Step four is about improving the weaknesses outlined in the previous step (output). Hence cost analysis of the indicators that needs to be improved versus the budget available for the project should be initialised.

3.3.1 Further application of the tool with Cost-Benefit Analysis (CBA) method

Following USPeAR assessment of the sustainability performance of each case study (e.g. substandard to exemplary), the question is now how to improve the weaknesses? Additionally, USPeAR gives a hierarchy of needs based on the weightings given and these must be considered also.

Kaliampakos et al., (2016) states that *"At the end of the day it all comes down to the cost"*. The author highlights that this becomes important when a project has to be assessed to take the ''go" or the ''no go" decision, considering that a project should be at a competitive level of efficiency in comparison with its alternatives. Nowadays, utilisation of underground space is essential and has become a vital part of urban areas development, as highlighted in the literature (Durmisevic, 1999; Kaliampakos and Benardos, 2008; Bobylev, 2009). However, underground constructions have proven historically to incur a higher capital cost when compared with the surface projects, which is an unfavourable beginning point (Kaliampakos et al., 2016). Hence, the cost associated with an underground project is a key element included in every project (Kaliampakos et al., 2016). A comprehensive assessment process is required to consider all criteria yielding costs or benefits.

On the other hand, considering that cost is a critical issue in the entire project, it is suggested to use CBA method to identify which of the indicators/alternatives should be supported? Based on the prognosis of which choice is likely to be beneficial in the long term? Cost benefit analysis is a popular and very widely adopted method that provides a consistent procedure for evaluating decisions in terms of their consequences (Drèze and Stern, 1987).

Combining the result of the USPeAR (poor performance indicators) with CBA, allows decision makers to have to have a clear overview of what difference indicators/alternative would make. There are several basic steps involved in conducting a cost-benefit analysis as described in 3.3.1.1 to 3.3.1.3 (Holland, 2012).

3.3.1.1 What is CBA?

Cost–benefit analysis (CBA) facilitate decision-making regarding selecting best option for a given situation. It is also useful for decision-makers to assess positive and negative economic effects of a project or policy by measuring relevant impacts of physical and monetary values (Chang et al., 2012; Wang et al., 2016). It evaluates advantage and disadvantages of a project, in a rational and systematic way, by assessing at least two options “do it or not” (EC, 2008; Ninan, 2008; Jones et al., 2014). Decision makers must evaluate who are the losers and who would this beneficial to, across both time and space (Ninan, 2008).

CBA will give an understanding of the costs of improving performance of the indicators that performed poorly, against the benefits which can be achieved by improving them. With a view to providing a comprehensive picture of the cost of various underground indicators, an attempt is recommended to be made to collect and present data, via meeting with stakeholders regarding the cost of underground infrastructure development. In addition, the estimated benefit from improving an indicator/ alternative in the future should be canvased from stakeholders.

3.3.1.2 The application of CBA

Through reviewing the literature, several studies have been found assessing the cost of underground projects, where it has been widely used in public decision-making on infrastructure investments (see for example, Asplund and Eliasson, 2016). In fact, the contemplations regarding the subject of CBA in urban public transportation systems started 25 years ago (Godard and Hugonnard, 1989; Girnau and Blennemann, 1989).

A case study conducted by Wang et al., (2014) utilised CBA for train improvement in Bangladesh. The authors considered three alternatives for making the improvement. Benefits were evaluated in terms of users' costs savings and emission reduction savings. The costs of alternatives have also been calculated in terms of capital, construction costs, operation and maintenance costs. The study revealed that Net Present Values (NPV), defined in the next section, is positive when considering a discount rate of 15%. Al-Tony and Lashine (2000) used CBA on a railway line electrification in Egypt. The research included potential benefits of the proposed system along with its costs. The duration of the appraisal was considered to be 30 years, including four years of construction work. The study used a 10% discount rate to achieve a positive NPV. Larsen (2016) evaluated the costs and benefits of improving electric utility reliability of underground electricity transmission and distribution lines. The analysis included three scenarios with 75, 60 to 45 years appraisal and a constant 10% discount rate. However, the results discussed to be sensitive to the choice of discount rates.

The innovation in UUS development and infrastructures that can be placed underground, goes beyond conventional thinking. For instance, Okorji and Ezeike (2000) utilised CBA to assess the economic viability of using modern underground facilities for storing yams comparing to the traditional storage in barns.

After briefly reviewing the application of CBA in underground and construction projects, as well as some of its modern applications, the next section explains the process for CBA calculations.

3.3.1.3 Method steps used for conducting CBA analysis

The following steps are mentioned by Söderqvist et al., (2015) and Reniers et al., (2016) for undertaking CBA analysis:

A. Identification of all costs and benefits;

B. Calculation of the Net Present Values (NPV) of all costs and benefits;

C. Comparison of the total NPV of costs and total NPV of benefits.

Hence considering the aforementioned steps, NPV is calculated using equations 3.1 to 3.3:

Equation 3.1

$$\mathrm{PV}(B_i) = \sum_{t=0}^{r} \frac{1}{(1+\ r_t)^t} B_{it}$$

Equation 3.2

$$And\ PV(C_i) = \sum_{t=0}^{r} \frac{1}{(1+\ r_t)^t} C_{it}$$

Equation 3.3

$$NPV = \sum_{i=1}^{N} PV(B_i) - \sum_{i=1}^{N} PV(C_i) = \sum_{t=0}^{T} \frac{1}{(1+r_t)^t}(B_t - C_t) - I_0$$

Where the terms have the following meaning:

Cost (at time t) = C_t and Benefit (at time t) = B_t

Present Value - PV (B) and PV (C) are sums of benefits and costs at time t (usually years),

r_t is the discount rate at time t, and

T is the time horizon associated with N benefits and costs.

I_0 is the initial cost of development of the proposed project

Following the above equations, the requirements of the CBA are:

1 Identification of all costs and benefits of proposed alternative (economic cost within this research)
2 Identification of the time frame of appraisal
3 Consideration of the effect of time on the proposed alternatives
4 Consideration of the impact of discount rate

3.3.1.3.1 Evaluation period or asset life of the structure

The evaluation period (i.e. time frame of appraisal) indicates the duration of the time over which the costs and benefits of projects are evaluated. For example, for a transportation project, the impact of project over time, as the project goes through different stages of development, i.e. construction, operation and maintenance. Hence, the evaluation period should incorporate both the physical life and the time taken to complete the project (Lah, 2002).

Different studies have investigated the appropriate evaluation period for CBA analysis, usually measured in years. For instance, Campbell and Brown (2016) argue that anything from one to 20 years is normal, however, some projects have longer lives (up to 50 years or more), depending on the nature of the project and the usefulness of the asset, while some analysts may find one year satisfactory to evaluate costs and benefits (Cellini and Kee, 2010; Söderqvist et al., 2015; Reniers et al., 2016).

Compared to other infrastructures, UUS has a relatively long life span. Some projects, such as Metropolitan and Statewide (National Research Council, 2013), consider the costs and benefits of investment for only a 20-year horizon. However, this evaluation period means that benefits occurring after 20 years are not counted in the decision-making. Tsimplokoukou et al., (2012) suggested that the reference evaluation period for railways is 30 years. ITA (1987) has shown some studies of underground construction considering evaluation period of 10 to 50 years. Longer evaluation periods have been considered, for example Girnau et al., (1982) considered 30 years for a CBA on urban railway construction. Furthermore, Foster and Beesley (1963) estimate the benefits of constructing an underground railway in London within 50 years.

In order to choose the evaluation period for the case study of this research, Aghdasiyeh Station staff have been consulted and it was reported that all the planning for the station is provided for the next 30 years. Hence, within this research a 30-year evaluation period been considered. However, additional one year has been considered for construction of the proposed alternatives, meaning that the overall period is equal to 31 years.

3.3.1.3.2 Discount rate

In order to calculate CBA, the NPV of the total cost and benefits (overall cost and benefits over time) has to be calculated. This could be facilitated by applying a discount rate. This factor informs the fact that the money spent or received in the future is worth less than the money spent or received today (Kaliampakos et al., 2016). In other words, discount rate is the difference between the rate of the return on the open market and annual inflation (Lampe et al., 2005). Discount rate is also defined as the inflation rate to consider how the money would alter in the future (Brzozowska, 2010 and Araújo et al., 2016).

According to Belay et al., (2016), a methodological consideration with respect to CBA is that it stretches over time. Time can influence human preference, and accordingly their choices among different alternatives. Therefore, the future benefits and costs have to include a discount calculated at some discount rate. In this regard, it is important to use and formulate the right discount rate, based on the type of the project and its location, as the inflation will differ (Söderqvist et al., 2015; Reniers et al., 2016).

The choice of discount rate can have a significant impact on the NPV and, hence, the output of the CBA analysis (Kazlauskienė, 2015). Considering a high discount rate will result in a low value on costs and benefits in the future relative to the present. For instance, a project incurring a high initial cost, but with benefits starting in a far future with a high discount rate, will look less desirable when compared to its evaluation at a low discount rate. The opposite is also true, for example, when there are short-term benefits but major costs to be incurred in the future. This shows that the choice of discount rate plays an important role when choosing the best alternative, hence, there should be a rational basis for choosing a specific value (Flory, 2013; Kazlauskienė, 2015).

Works previously done by several authors have been reviewed and it was found that the discount rate was assumed to be the same as inflation rate (see for instance, Brzozowska, 2010; Söderqvist et al., 2015; Araújo et al., 2016; Reniers et al., 2016). Hence, for Aghdasiyeh Station in Tehran, one of the utilised case studies, the discount rate was selected the same as Iran's inflation in 2015; 8 % (Trading Economics, 2017). However, it is common to conduct a sensitivity analysis with higher and/or lower variations on the selected rate to identify the margin for error, which would limit the relevance of NPV for other similar projects to be taken as a benchmark (Department of Transport, 2011). And, hence, a discount rate of 7.3% and 12.6%, inflation rate for 2007 and 2018 respectively, has been considered for the sensitivity analysis (Trading Economics, 2017) (Section 6.3.3.4).

If CBA is used, the recommendation on whether to accept or to reject an investment project is based on the following process within an investment project (Söderqvist et al., 2015):

- NPV > 0 means that the project will result in a positive benefit compared with current expectations;
- NPV = 0 means that the project will just meet expectations;
- NPV < 0 means that the benefits are lower than expected.

The option with the highest NPV is the most profitable one.

3.4 Demonstration of the Framework: Case Study Choice and Justification and Tool Validation

Case studies are used to ascertain the reasons why a decision or a set of decisions has been adopted, the procedures of implementing the decision and the results for applying such decision (Schramm, 1971; Ahmed, 2002). According to Yin (2003), "*A Case study is an empirical inquiry about a contemporary phenomenon (e.g., a "case"), set within its real-world context especially when the boundaries between phenomenon and context are not clearly evident*".

Case studies as a way of testing and/or validating theoretical frameworks have been widely used and reported in the literature (Zainal, 2007). They are considered as a robust research method, especially when a holistic in-depth assessment is needed. Using case studies, the examination for both qualitative and quantitative data can help to explain the outcome of the assessment through complete observation, reconstruction and analysis of the cases under investigation. However, this method has been criticised for providing little basis for scientific generalisation since they are limited only to a few subjects within one main and it has been challenging to generalise from a single case (Yin, 2003; Zainal, 2007; Al-rubaee, 2012). Yet, in this study a generalisation was not required and the case studies are used for validating the proposed tool.

Overall, case studies are preferred methods when the researchers are dealing with 'how' and 'why' questions and they are intended as a means by which to investigate existing complexities within some real-life decisions (Ahmed, 2002; Yin, 2003). A case study is also a methodology that benefits from prior development of theoretical propositions to guide the design, data collection and data analysis approaches and techniques (Stoecker, 1991). Hence, this method has been selected to show the application of the developed tool and to validate the use of the designed USPeAR tool.

For this research, two case studies were considered, which are explained in Section 3.4.1 and 3.4.2. This research, within the case studies, has utilised the knowledge of project stakeholders whose jobs are related to civil engineering, such as contractors, designers, decision makers and sustainability specialist. The case studies have been done by holding meetings with those specialists in the project, where the USPeAR assessment in the form of graphic representation was given. In addition, a comparison between USPeAR and original SPeAR® was presented and the benefits of utilising USPeAR discussed during those meetings.

3.4.1 Case study 1: Farringdon Station, London, UK

The first case study undertaken in this research is Farringdon Station in London, UK. Farringdon Station has been a successful project from a sustainability point of view, and has been awarded 'excellent' from CEEQUAL assessment tool (CEEQUAL, 2016).

The case study was selected for two specific reasons:

1) To verify the results of USPeAR and to compare the results with CEEQUAL;
2) To use it as a benchmark for a second case study (i.e. Aghdasiyeh Station); since Farringdon Station is assumed to have an excellent performance, it aids the process of scoring Aghdasiyeh against an excellent performance project, and also provides an opportunity to draw some ideas for Aghdasiyeh improvement.

USPeAR tool has been tested on the project and in order to assess the case study, the selected indicators (presented in Chapter 4, Table 4.5) with guided questions from original SPeAR® were prepared and discussed with experts involved in Farringdon Station project. Overall a total of 6 hours of meeting were arranged on three different days. The initial meeting was held at Farringdon Station office with Mr Simon Miller and the subsequent meetings were held with Miss Francesca Pacifico and Mr Mike de Silva (Head of Sustainability of Crossrail). The indicators have been discussed and narratives produced for each indicator were used at each of the three meetings. Based on the evidence presented by the experts a score reflecting the group judgment was given to the indicator sets.

3.4.2 Case study 2: Aghdasiyeh Station, Tehran, Iran.

The second case study applies USPeAR to an underground metro line in Tehran, Iran. The reasons behind selecting this case study were mainly due to the following factors:

1) There is not a robust sustainability agenda in Iran, hence, the station was predicted to perform poorly. This facilitates the opportunity to compare the results with Farringdon Station which was known to perform excellently;
2) It has the advantage of comparing the tool application for two countries with different sustainability agendas and to prove the worldwide application of the tool;
3) The poor performance of the project shows the application of the tool, as well as the application of CBA method for improving the project.

When viewed in combination the results of the two case studies represent two extremes of sustainability in underground space. In a similar process to the first case study, indicators and guided questions were prepared and discussed during a number of meetings held on two different days on July 2016. Overall 8 hours of meeting were held with Mr Shahab Karimi and Mr Behzad Amirfard whose roles were as technical coordinator and head of business development of the Tehran metro respectively. According to the discussion and evidence presented in the meetings, a final score was agreed and given for all of the indicator sets.

3.4.3 Tool validation

Subsequent to the development of the tool and utilising it for two case studies assessment, the next task is to assess the validity of the tool. The tool has been further validated using the first case study, which has been previously assessed by CEEQUAL. The result of CEEQUAL showed that Farringdon station performs excellently.

The CEEQUAL assessment is done in nine categories:

- Project/contract strategy

- Project/contract management
- People and communities
- Land use (above and below water) and landscape
- The historic environment
- Ecology and biodiversity
- Water environment (fresh and marine)
- Physical resources use and management
- Transport (CEEQUAL, 2016).

However, according to CEEQUAL, Farringdon Station has been performed excellently with respect to the following categories, which are sub-indicators of aforementioned nine categories: heritage and town planning requirements, noise and nuisance, piling into the aquifer, designing out waste, community relations and engagement, energy and carbon, material use and sustainable procurement, and ecological habitat creation.

Further the USPeAR tool will be tested on Farringdon Station and the validation by CEEQUAL will be explained in discussion Chapter 7 (Section 7.3.2).

3.5 Summary

This chapter has reviewed the methodology undertaken to conduct this research. In order to assess the contribution of UUS towards sustainability, a tool has been developed. The development of the tool comprised three elements; a literature review, which revealed that at present there is no comprehensive sustainability assessment tool specifically for underground space and highlighted SPeAR® as the most appropriate tool for the purpose of this research to be modified. A final set of indicators for three pillars of sustainability have been selected with provided appropriate justification. Next, the weightings were developed through a questionnaire and use of expert panel. All these have been put into the excel spreadsheet in a form of tool providing graphic representation. In addition, case studies have been used to test the tool, which is evidence of how the tool works, what it offers compared to original SPeAR®, and how it could be beneficial to UUS construction. A further step is coupling CBA with USPeAR results, when further improvement has to be made to the project.

Detailed descriptions of each module explained in this chapter are presented in Chapters 4 to 8.

CHAPTER 4: DEVELOPMENT OF THE SUSTAINABILITY ASSESSMENT TOOL

The knowledge obtained from literature review (Chapter 2) has reinforced the need for a new sustainability assessment tool specific to UUS. This chapter reviews, justifies and subsequently modifies the most suitable tool, SPeAR® for the purpose of this research to develop a new specific UUS tool (with a set of indicators with weightings attached) which is the ultimate aim of this research.

This chapter addresses objective three of this research by:

- Reviewing SPeAR® system and its associated advantages and disadvantages
- Modifying SPeAR® system specifically for underground space use
- Introducing a new set of indicators with justification of why and how it could be applied UUS.

4.1 Development of UUS Indicator Sets

An indicator system (developed for subsurface use) should help to measure how well a system is working, and provides a clear understanding of what might be achieved regarding the future targets and how far the project is from achieving these goals (Hunt et al., 2007). Therefore, to develop an indicator system for UUS, it is important to consider sustainability as a long-term resolution. The contribution that underground systems make to sustainable development should be broken down into smaller units of assessment criteria so that UUS performance can be analysed and measured in detail to facilitate the sustainable decision-making processes from the start of a project through to completion and ultimately long-term use (Jefferson et al., 2007). In the next section, a base tool SPeAR® was selected, modified and used for the new UUS tool.

4.2 Rationale for Selecting SPeAR®

In order to develop a specific UUS assessment tool, the author has reviewed existing sustainability tools applicable to construction projects with a purpose of being able to understand whether any are appropriate for direct use or modification (Chapter 2). SPeAR® has been selected for direct modification because out of all the methods reviewed it constitutes a holistic approach, which is easily understood and specifically would allow straightforward modification for sustainability assessment of underground space use. Specifically, as mentioned by Holt et al., (2010), SPeAR® is not award-based and therefore does not have an in-built bias. The principal idea of the tool is to recognise the areas that can add real benefits or sustainability improvements to a project. The assessment underlines and compares the strengths and weaknesses of the project, and aims to help improve the sustainability. The framework provides a starting point to present overall current performance of the project in terms of sustainability either to the internal or external stakeholders (Braithwaite, 2007). The design approach can then be optimised to produce a more sustainable outcome.

Pearce et al., (2012) state that SPeAR® is a comprehensive tool based on a large number of commonly accepted indicators, such as UK Government's set of sustainability indicators and its sustainability strategy. This is a significant advantage. Moreover, its transparent formulation allows it to be modified and created for different contexts. ASPIRE is a downloadable version of SPeAR® formulated for developing countries (Arup, 2015b).

However, there are those such as Donovan et al., (2005) that have criticised SPeAR® for being over simplified and therefore too flexible in its approach. Having said that, this could be considered as a significant benefit for this research. Providing enough flexibility allows individuals to create desirable indicators or sub-indicators as well as removing and modifying them – in this case for application on UUS projects. Therefore, SPeAR® is a simple framework which offers adequate flexibility to allow modification for specific projects such as including or excluding indicators and whilst it is non-weighted the opportunity to add weights can be explored.

The main features of the SPeAR® framework can be summarised as below (McGregor and Roberts, 2003):

- It gives a graphic presentation (Figure 4.1) of the project during all stages, indicating strength and weaknesses therein;
- It allows the various aspects of sustainability to be optimised and the inter-relationship of these to be assessed;
- It identifies where there may be room for improvement in order to achieve optimum benefits;
- The logical and transparent methodology is fully adaptable for various applications;
- It demonstrates the interaction between the various social, environmental, economic indicators of sustainability;

- The spreadsheet behind the SPeAR® diagram ensures that all assessments are fully audit traceable – and therefore easily modified;
- It prompts innovative thinking to include sustainability into project design and demands team coordination and consensus.

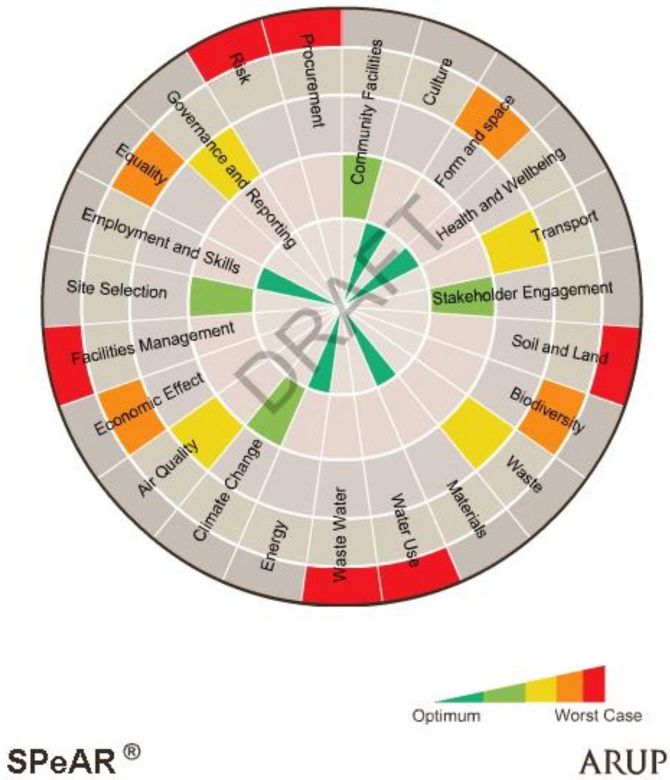


Figure 4.1: SPeAR® full diagram (Arup, 2012)

SPeAR® has been produced with the goal that it can be utilised to screen and assess project execution and aid informed decision-making all the way through the project lifecycle.

- *At the beginning of the project*, it can be used to perform baseline assessment, gap analysis or highlight the key performance indicators, Key Performance Indicators (KPIs) that reflect a project's goals. SPeAR® can also provide the means for the measurement and management of progress towards those goals for further learning and improvement (Kylili et al., 2016).

- *During design stage*, it can be utilised to compare and contrast the advantages and disadvantages of different design choices, distinguish key risk areas, help decision-making and stakeholder participation or assess the implications of design change.
- Alternatively, it can be utilised to carry out assessment *upon task fulfilment as well as during operation*. This could be useful to inform organisational learning and approaches to future projects (Arup, 2012 and 2015).

4.3 SPeAR®

4.3.1 Indicators and sub-indicators

The original SPeAR® diagram encompasses a series of detailed worksheets, with over 120 sub-indicators of social, environmental performance and economic (Arup, 2012; Arup, 2015a and b). Each core indicator is broken down into sub-indicators, which represent more specific sustainability topics (see Figure 4.2). The indicators are demonstrated using a 'wedge' within the SPeAR® diagram as shown in Figure 4.3. The indicators presented within SPeAR® have been extensively reviewed by different professions to ensure their applicability and relevance. The main objective of SPeAR® is to integrate sustainability issues within built environment projects. However, it fully recognises that certain projects will need changes within the indicator sets that have been developed. This is an essential component as a part of the tool that provides project specific compatibility (Holt et al., 2010).

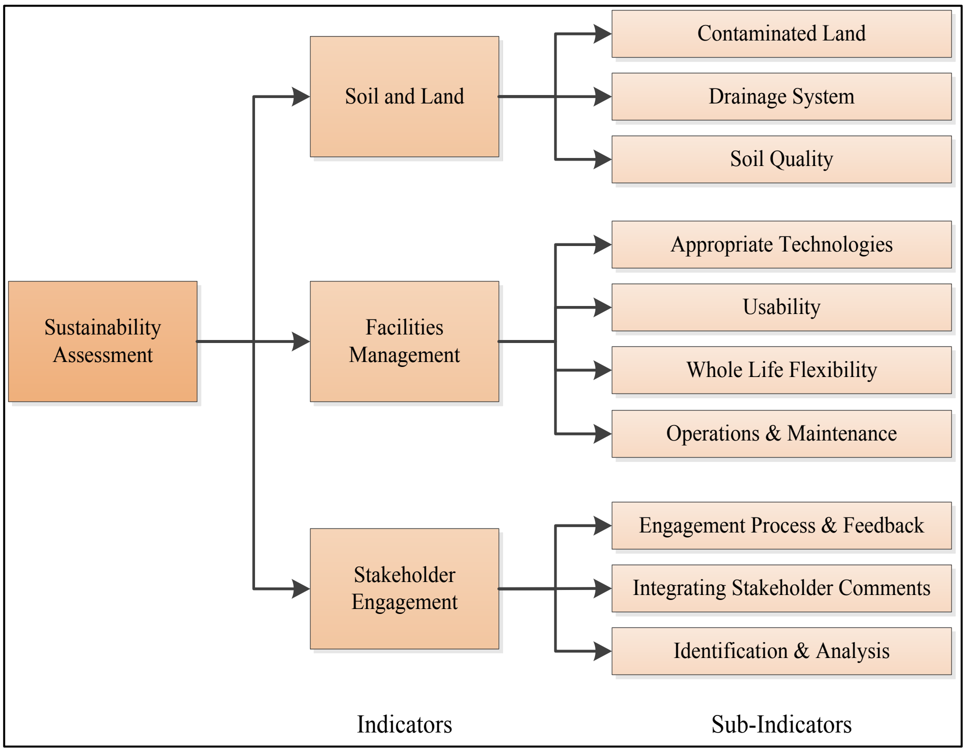


Figure 4.2: Conceptual representation of SPeAR® indicators and sub-indictors (Arup, 2012)

4.3.2 Rating/scoring system within SPeAR®

To undertake a SPeAR® assessment, the sub-indicators are assessed by means of what is called a SPeAR® performance rating. The sub indicators are allocated a best and worst case description. Figure 4.3, represents the SPeAR® performance rating system for indicators. It comprises five different rating levels from +3 (dark green) to -1 (red). Braithwaite (2007) compares the diagram with a dartboard, and describes the main aim as being to have as many segments as possible close to the centre. Information shown on the diagram is a direct reflection of the quality of information available at the time of data collection, which is used to complete the worksheets. In order to score the indicators, a detailed set of specific questions are provided alongside SPeAR® indicators, Project teams, help to determine allocation of the specific scoring that each sub-indicator should receive (Arup, 2012).

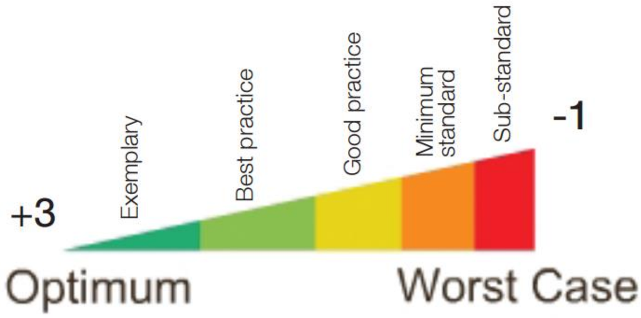


Figure 4.3: SPeAR® rating system (Arup, 2012)

4.3.3 Materiality

There is an opportunity for the team to include relevant indicators or exclude irrelevant indicators. Within SPeAR®, this is defined as a *'materiality review'*. SPeAR® provides a set of additional indicators alongside the core indicators and sub-indicators, which could be included (subject to a materiality review having been undertaken). This allows the SPeAR® tool to be specifically tailored to each and every project. It is important to remember that a sustainability professional should assist with the materiality review. According to the SPeAR® manual, materiality is classified into five main categories of:

- Risk
- Legal/regulatory/internal and external policy drivers
- Stakeholder concerns and societal trends
- Opportunity for innovation
- Best practice/Peer-based norms

Based on these categories a justification (based on either qualitative or quantitative assessments) has to be made on all the indicators (Arup, 2012; Boyko et al., 2012). Based on SPeAR® each category of materiality is described as following:

Risk: Indicators and sub-indicators that can contribute to any possible financial, social and environmental risks, however minimal the risk may seem, have to be included. It is vital to consider all the issues that may present a risk.

Legal/regulatory/internal and external policy drivers: The purpose of this step is to consider indicators and sub indicators that can relate to any policy or legislation within the country or region where the project is taking place. This helps the assessment to consider the most up-to-date legal and policy requirements.

Stakeholder concerns and societal trends: This ensures that indicators which are vital to stakeholders, including communities, non-governmental organisations and the public, and/or reflect social and consumer trends to be considered.

Opportunity for innovation: It is essential to make sure indicators are not excluded based on the limited negative impact, if the project has an opportunity to innovate and create a positive sustainability impact. This helps push the boundary of sustainability on a project.

Best practice/Peer-based norms: It is significant that indicators demonstrate the current practices within the industry that a project is implemented. This helps to include issues that are reported by industry as current global best practice into the assessment.

4.4 SPeAR® Modifications

This section demonstrates the process of modification that has been made to SPeAR® for UUS use. The first step is the selection of appropriate sustainability indicators. The materiality review undertaken for the UUS tool development will be described (Section 4.4.1). Thereafter SPeAR® has been assessed to see whether an indicator is appropriate (or not) to the overall development within UUS. As part of this process applicable indicators are provided with a narrative that describes specifically how it relates to UUS.

4.4.1 Materiality review

A qualitative materiality review, with the help of the author and Mr Peter Braithwaite (in the form of yes/no), has been undertaken (as explained in Section 3.2.1), which is presented in Appendix A. Based on materiality review, relevant indicators to UUS were selected and indicators that were deemed to be irrelevant were excluded. A thorough review of the literature provided a narrative and UUS examples for each indicator as well to clearly explain the relevance of the indicators to any underground project. The narrative is helpful when considering whether the indicator is relevant. The summary of the materiality review and a synopsis of who was involved is shown as follows:

Risk: Risk associated with indicators according to SPeAR® with respect to financial, social and environmental aspects have been studied and reviewed from the evidence base in literature and brainstorming meetings with Mr Peter Braithwaite. This can be found in Appendix A.

Legal/regulatory/internal and external policy drivers: Different regulations for underground constructions have been studied such as Transport for London, Crossrail and HSE. Indicators were selected if they have been mentioned in the regulations.

Stakeholder concerns and societal trends: Stakeholders of underground space are public, design engineers, construction manager, owner agency and contractors (Edgerton, 2008). It has been aimed to look at indicators from the stakeholders' point of view and chose the most relevant indicator.

Opportunity for innovation: Brainstorming based on the literature and previous experiences has been done through meetings Mr Peter Braithwaite, during previously mentioned meetings, to see if any indicators can pose a different impact or provide an opportunity for the betterment of an underground facility.

Best practice: Through literature review, research has been done to find evidence of best practice of the indicators performed in underground space constructions. References have been provided in the following section where appropriate.

The narratives provided for the indicators are as follows:

4.4.1.1 Environmental pillar

Table 4.1 illustrates the indicators in the environmental pillar of SPeAR® and provides comments on their relevance to UUS use.

Table 4.1: SPeAR® environmental pillar

Core indicators	Sub-indicators	Comments
Soil and land	Contaminated land	Appropriate
	Soil quality	Appropriate
	Drainage systems	Appropriate
Biodiversity	Protected species and habitats	Appropriate
	Conserving and improving local biodiversity	Appropriate
	Habitat connectivity	Inappropriate
Waste	Construction waste management plan	Appropriate
	Waste in operation	Appropriate
	Hazardous/special waste	Appropriate
	Designing out waste	Appropriate
	Composting	Inappropriate
Materials	Materials efficiency in design	Appropriate
	Use of recycled or reused materials	Appropriate
	Environmental and sustainability impacts of materials	Appropriate
	Healthy materials	Appropriate
Water	Water pollution	Appropriate
	Water resources	Appropriate
	Wastewater treatment and disposal	Appropriate
	Water monitoring	Appropriate
	Water supply	Appropriate
	Construction	Appropriate
Energy	Energy supply	Appropriate
	Energy conservation and efficiency	Appropriate
	Energy monitoring	Appropriate
	Daylighting	Appropriate

Climate change	Carbon management plan	Appropriate
	Social impact of climate change	Appropriate
	Physical impacts of climate change	Appropriate
	Carbon sequestration	Inappropriate
	Economics of climate change	Appropriate
Air quality	Ambient air quality	Appropriate
	Direct emissions	Appropriate
	Indirect emissions	Appropriate
	Ozone depleters	Inappropriate

1. Soil and land

Contaminated land: For a UUS project, consideration has to be given to contaminated land that has solid or liquid substances mixed with soil. This sort of contamination could be the result of tank or product leakage, which can lead to environmental pollution. For example, Sayigh (2014) states how pipe works underground can lead to soil contamination. Considering this indicator will help an underground project to be checked regularly to avoid contamination.

Soil quality: This is allied to the above indicator and is fundamental for a smart and safe design of any underground structures. For a sustainable underground project, there is requirement for having a clear understanding of the soil and rock mechanical properties at and near a project site (National Research Council, 2013). Considerations have to be given to geological soil types and the history of loading, and whether there is a risk that can lead to temporarily or permanent change to soil properties during underground construction or operation. For instance, ground freezing can temporarily turn a weak, saturated soil into a solid and nearly impermeable material; dewatering can ease construction problems both in terms of water flow and soil stability (National Research Council, 2013). This indicator inclusion brings opportunity to assess sustainability of underground project with respect to soil conditions.

Drainage systems: For any underground project, the drainage system and ground water level need to be considered. There is a risk of groundwater intrusion into facilities or groundwater-induced corrosion of the facility structure itself. In this respect, new materials for sealing underground structures or self-sealing of leaks or cracks would help to keep groundwater out of structures, and an innovative design can integrate drainage water into the energy concepts for the facility (National Research Council, 2013). An underground facility can be examined against this indicator to improve sustainability aspects of any existing or proposed drainage system.

2. Biodiversity

Protected species and habitats: This indicator measures the impact that the project may have on the surrounding habitats and species. It concerns areas that are protected by national or regional regulations and need to be kept protected. Construction activities can greatly affect local and global diversity and use changes can affect habitats and species. For example, for London Underground (LU), there is a biodiversity action plan and there is legislation to protect species and habitats. Including this indicator helps to consider and improve habitats life (Transport for London, 2010).

Conserving and improving local biodiversity: Biodiversity refers to the variation of living things of the earth, from mammals to insect and trees and the habitats in which they live. It includes the diversity of species, genetic variability within a species, and their interactions with the environment. The Earth's biodiversity is an important component for maintaining natural balance and sustaining ecosystems (Transport for London, 2011). Our activities can significantly affect local and global biodiversity and may lead to loss of biodiversity. For example, part of London Underground plan is to conserve, and where reasonably practical, to enhance the biodiversity value of LU property (Transport for London, 2011). Therefore, adding this indicator will help any project located underground to be considered with respect to biodiversity and improvements that it can make in this respect and include measures that can enhance biodiversity.

Habitat connectivity: This indicator examines the links between various habitats, which are important for species to survive and develop (Arup, 2012). Wildlife connectivity mostly occurs on the surface rather than underground. However, for the ones that live underground such as rabbits, considerations have been given in the above two indicators (protected species and habitats and conserving and improving local biodiversity) which means that inclusion of this indicator is not necessary.

3. Waste

Construction waste management plan: Waste minimisation is important to achieving good waste management (Transport for London, 2006). This indicator is about having a waste strategy and a target to reduce, reuse or recycle waste during a construction (Arup, 2012). For example, Transport for London (2006) mentions that they are committed to waste minimisation, alongside the exploration of further opportunities for waste recycling. In addition, they provide a plan for the waste collected and recycled and a target for waste recycling is set regularly. As an example, wooden sleepers in tube lines are replaced with concrete ones, which have a longer asset life, thereby reducing waste (Transport for London, 2006).

Waste in operation: Similar to above for underground construction projects, the waste produced from the (in operation) use of UUS infrastructures has to be dealt with. A wide variety of wastes can be produced by operating and maintaining underground services. Within the rail industry, these wastes include customer waste, station and depot waste and waste associated with station, track and infrastructure projects (Transport for London, 2006). This will require operators to improve the environmental profile of the materials they use, reduce the amount of waste associated with the activities being undertaken, and recycle more of the waste that is produced. Established indicators will need to be adopted for each area, monitoring, and reporting on performance will be required. For example, Tube Lines collect waste from all stations, depots, and some of offices (Transport for London, 2006).

Hazardous/special waste: To have a clear understanding of any hazardous materials that can be released or transported during UUS construction is important for long-term sustainability. There is a risk that hazardous materials produced during underground construction can add increased unexpected cost to a projected as well as delay to project delivery. Thus, it is important to characterise hazardous material (e.g., chemical contamination and radiation) and their effects on the natural and built environments for particular construction and operation activities (Department for communities and local government and chief fire and rescue adviser, 2013). For example, Transport for London (2006) states that at depots and sidings, containers are provided for the separate collection of hazardous materials, such as fluorescent tubes and waste oils.

Designing out waste: This indicator considers having a site waste management plan during design phase of a project and considering the need to reduce potential waste (Arup, 2012). Burland (2012) describes that an efficient geotechnical design makes optimum use of construction materials and hence reduces the impact on natural resources. Similar to any construction project, UUS projects are inextricably linked and dependent on geotechnical design therefore the need to develop a clear plan for minimising the amount of the waste and for managing the generated waste is highly relevant and necessary.

Composting: Composting is the highest form of recycling. Organic wastes such as grass, vegetation, or food can be re-used and returned to land for the purpose of fertilization. They can go through anaerobic digestion so can be used as energy and fuel (Epstein, 1997). However, UUS facilities do not generally have vegetation waste, which leaves food wastes, and there is no evidence of a facility located underground with composting services, therefore this indicator could be considered inappropriate and therefore excluded.

4. Materials

Materials efficiency in design: This indicator is about investigating if the design process has considered the appropriate specification of the construction materials adopted for geotechnical structures. This includes choosing the right material, reducing material consumption through either weight or downsizing, less use of non-recyclable material and therefore improving design over the lifecycle of the project (e.g. durability and strength) (Arup, 2012). This indicator is applicable to any construction project either underground or above ground.

Use of recycled material: This indicator considers if reused or recycled materials have been considered for potential use. Alternatively, to check whether the design provides for a materials inventory to enable future reuse or recycling (Arup, 2012). Consideration of the environmental impact and appropriate choice of material for any geotechnical infrastructures is essential. For example, choosing steel rather than concrete as a structural material require specification of a minimum requirement for recycled content of steel and steel reinforcement (Burland, 2012). Therefore, this indicator is applicable to UUS as well as above ground construction.

Environment and sustainability impacts of material: Within this indicator, the aim is to select materials, which minimise environmental and sustainability impacts. This can be done through use of an appropriate material rating system (e.g. the UK's BRE Green Guide for material specification). Additionally, the indicator investigates if the design demonstrates the use of appropriate indicators (e.g. embodied CO_2) to evaluate and improve the environmental (embodied) impact of materials (Arup, 2012). The most commonly used material in UUS projects is concrete. For example, a key element of the sustainability initiative for the tunnelling industry, primarily to reduce carbon costs, is to significantly reduce the volume of high carbon cement. Therefore, it is not uncommon to hear of a specification for 55-60% (or more) cement replacement material content to be adopted in concrete mixes (Penrice and Townsend, 2010). Therefore, this indicator should be considered for UUS construction.

Healthy materials: This indicator examines whether the toxicity of materials to be used on the project have been considered. Checks are required to determine if the materials selected have impact on indoor air quality (e.g. paints, flooring, glues) or on manufacturers, construction workers and project occupiers (Arup, 2012). For example, Transport for London (2014) reviews all materials and their health impacts for London stations. Therefore, this indicator is considered a relevant indicator to UUS construction.

5. Water

Water pollution: Water is an important part of geotechnical engineering and is a fundamental requirement for UUS projects during and after construction. UUS projects can result in changes to groundwater (in quality and the actual level of the water – not least if abstraction during construction is implemented) all of which can cause ground movements and impact on UUS structures (Burland, 2012). One of the considerations for any infrastructure (in its broadest sense) located sub-surface is to ensure that groundwater is not contaminated either directly or indirectly during construction or other manmade activities. An increasingly common form of groundwater contamination results from the presence of dissolved and/or free petroleum products within the ground during tunnelling. Such contamination typically results from leaking underground gasoline storage tanks, and can be quite extensive and concentrated (Klingler et al., 2002). Therefore, this indicates that for a facility to be located underground this indicator has to be considered.

Water resources: This indicator relates to the consideration of water resources. For example, whether the project is located in a water scarce area, or whether there is a restriction on water use, or how will the future development of the project affect availability of the water (Arup, 2012). One of the main concerns for UUS projects should be its impact on existing water resources and their users (Burland, 2012). A case example of a groundwater model (as adopted for the Florence TAV station (Treno Alta Velocita)), is the damming effects that the underground station box construction has on the regional groundwater flow, within the shallow unconfined sand aquifer as illustrated by Heleni et al., (2012). This inclusion can enhance sustainability of an underground project in these terms.

Wastewater treatment and disposal: Clean water is one of the most precious commodities in the world (Parker, 2006). This indicator explores the methods that can be used for treatment of used construction or operational water. In addition, sewer systems contribute significantly to all projects and are a key delivery aspect of many, if not all projects (Arup, 2012). For example, Yi-Wen et al., (2012) discuss treatment and reuse of tunnel construction wastewater and the authors review wastewater characteristics and the methods of treatment. Therefore, regardless of underground and above ground construction this indicator is a key element.

Water monitoring: This indicator scrutinises if the water is monitored through meters and sub-meters and if plans are in place to manage water use or water loss. Leakage also needs to be controlled, for example through sensors (Arup, 2012). Young (1993) discusses how sensor could be used to monitor water flow into a tank for underground storage tanks. Water intrusion would be alarmed using a sensor places in the bottom of the tank. Similarly, water usage and disposal of waste water needs to be monitored during development of UUS infrastructures too. This is primarily due to the fact that water is usually present at some depth below the surface; and once encountered by man-made activities (e.g. tunnelling / basement construction) may produce flows of groundwater. Lindstrom and Kveen (2006) discuss the effects of groundwater leakage and develop procedures to quantify maximum allowable water inflow to a tunnel based on impacts on surface environment (e.g. defining the accepted leakage in urban areas which is related to possible soil settlement).

Water supply: The SPeAR® indicator assesses where the water supply is sourced from, for example water mains, lakes or rivers. Further, it investigates if the design minimises potable water consumption (Arup, 2012). Therefore, for either above or underground construction it is important to have enough information about water supply. For example, for the Library of Birmingham, which is a recent project greywater recycling system have been used (Dezeen magazine, 2013; Lomholt, 2014).

Construction: Based on SPeAR®, this indicator refers to the type of water used for construction phase of the project; the aim is to use the minimum amount of potable water and maximum amount of rainfall or untreated water or abstract it from a renewable source (Arup, 2012). Similar to above ground, for UUS construction it is a necessary indicator to identify the water for construction use within UUS.

6. Energy

Energy supply: This indicator investigates the source of energy, whether it is supplied from renewable or non-renewable sources (Arup, 2012). Hence, with respect to UUS construction (and operation/maintenance), as with above ground construction, this would require cognisance of a range of supply sources that move the project from relying solely upon fossil-based fuels (i.e. oil and gas) to one, which includes renewables.

Energy conservation and efficiency: All UUS projects, as with above ground projects, are energy intensive during both the construction and operation phase. During UUS construction, there is a requirement to reduce this demand through conservation and efficiency. During operation, there is a need to identify opportunities for greater efficiency or demand reduction. In the past two decades, ground source heat pump (GSHP) system (i.e. using energy below ground) has made a good impact on energy saving in Western and European countries in heating/cooling and industrial applications (Sivasakthivel et al., 2014). An example is presented by Library of Birmingham, in which GSHP have been used to extract heat from underground for energy saving purposes (Lomholt, 2014).

Energy monitoring: Based on SPeAR® this indicator relates to tracking energy use and monitoring energy conservation, for example through installing meters and sub-meters (Arup, 2012), which also applies to UUS. An underground facility can be improved by considering this indicator, particularly where long-term use of the facility is required.

Day lighting: This indicator explores the opportunities for using natural light rather than artificial light and if daylights measures have been taken into account to reduce the need for artificial light (Arup, 2012). While lighting is only one of considerations in the interior design of a building, it takes on a fundamental and multi-faceted importance in the design of UUS (Sterling and Carmody, 1988). Underground space lacks access to natural daylight and in underground facilities steps should be taken to ensure access to natural light whenever possible. For example, the provision of desired quantities of natural light can be achieved in UUS through specular reflectors, and correctly sized solar light pipes / wells / tubes (Bouchet and Fontoynont, 1996; Hunt et al., 2016). Recent example of where natural lighting has been provided in UUS projects in the UK includes Birmingham's Bullring (Makana et al., 2016). However, for deeper infrastructures, there is often no alternative to sole reliance on artificial lighting. This reliance on artificial light will require adoption of the most energy efficient lighting technologies (e.g. LED lighting reducing demand by 90% as compared to traditional lighting) in order to minimise the impact on energy consumption and carbon emissions (Hanamura, 1998).

7. Climate change

Carbon management plan: For the UK two of the main contributors to emissions are buildings and transportation, which produced 38% and 24% of the UK's emissions in 2009 (Department of Energy and Climate Change, 2011). There is a vision to reduce their associated carbon emissions by 2050. By utilising measures such as use of low carbon buildings and low carbon transport (Department of Energy and Climate Change, 2011). At a local level, Birmingham's Green Commission published its Vision Statement in March 2013, in which it has set a target to reduce total CO_2 emissions by 60% by 2027, against a 1990 baseline (Birmingham City Council, 2015). All of these are attempts to pick a pathway to achieve the low carbon transition. However, the role that UUS could play was not integral to this and this suggests that a fundamental consideration of all UUS projects should be higher up on the agenda. An example is Crossrail, which is set to calculate and reduce their carbon footprint through minimising the energy use (e.g. 8% reduction in construction related energy which is equal to 30,000t of carbon saved during construction stage) (Crossrail, 2016).

Social impact of climate change: This indicator is about threats and opportunities presented by climate change on people. There are undoubtedly issues regarding the social impact of climate change. For example, in the London Underground high temperatures are regularly experienced by passengers in hot weather, particularly during summer evening peak time. Temperature is the main factor affecting passenger thermal comfort, although air movement is also significant. The current ventilation system, based on fans and draft relief shafts is already inadequate for cooling the underground and therefore the indicator requirement here is to consider the advent of climate change and its impact on those that ultimately use UUS, whether it is for commuting, working or leisure purposes. This is fundamental to the success of UUS projects (Mayor of London, 2005).

Physical impacts of climate change: Climate change is increasingly testing the robustness of existing infrastructure (much of which is located in UUS) and building stock (Burland, 2012). The impacts of climate change within UUS could be direct or indirect. For example, sea level rise or intense rainfall could affect ground water and sea levels, significantly affecting existing or planned UUS construction. Therefore, this indicator ensures that robustness and longevity of the UUS project is more readily considered under changing climate conditions (Mayor of London, 2005).

Carbon sequestration: This indicator explores if the project has impact on woodlands, peat bogs or other carbon sinks and if the project can contribute new capacity for carbon capture and storage (Arup, 2012). Carbon dioxide can be permanently stored in deep underground spaces in geological formations. For example, in the UK, carbon dioxide will mainly be stored in deep rock formation (CCSA, 2016). It can be concluded that underground could be used for carbon sequestration, however; an underground facility unless specifically designed to do so does not bring an opportunity for this purpose. As such through the literature there is rare evidence of underground infrastructure providing the opportunity for carbon sequestration.

Economics of climate change: This indicator makes explicit if consideration has been given to the immediate cost of action of climate change versus the long-terms costs of inaction and if the risk related to the impact of climate change have been taken into account (Arup, 2012). For example, according to Mayor of London (2005), extreme weather in recent years has brought challenges to keeping London moving. Flooding, heatwaves and storms have all presented challenges to maintaining an efficient transport network. Therefore, it is planned to evaluate the potential *'risks'* of climate change, the consequent *'impacts*' and '*costs'* (e.g. of disruption) and identify how the management of the risks identified should be incorporated into transport management strategies (Mayor of London, 2005). This is as more applicable for UUS as it is for space above ground.

8. Air quality

Ambient air quality: This indicator examines if the local ambient air quality has been considered in the design of the project, if the ambient air quality is likely to affect occupiers/ users of the project, and whether ventilation has been considered for air quality (Arup, 2012). UUS has its own closed air quality system, since it is isolated from the atmosphere. Man-made constructions create their own air flow depending on the humidity and hence, it is required to control air quality below ground with either air conditioners or other ventilation means (Hoek and Hudson, 1993). For example, researchers have found that small dust particles in the air in an underground railway station is quite different to the dust breathed in most other surroundings and is suggested to be dangerous for people's health (Daily mail, 2013). This indicator duly considers these aspects and considers how air quality can improve the sustainability of a project in terms of occupiers' health.

Direct emissions (to air): This indicator concerns whether the project has a direct impact on the ambient air quality management strategy for the local area, and if the project has been designed to minimise human and flora/fauna exposure to air pollutants and if targets have been set to reduce emissions (Arup, 2012). Considering this indicator will help to improve air quality of an underground project. For example, Demir (2015) compares air quality in the underground and above ground multi-storey car parks in terms of exhaust emissions, which states the air pollution caused by vehicles has harmful effects with respect to human health specifically those produced in closed areas without adequate ventilation. The author further discusses the way to measure the emissions and to reduce them accordingly such as design and geometrical dimensions of the car park or automatic ventilations systems.

Indirect emissions: According to SPeAR®, this indicator investigates whether indirect emissions from the project (e.g. those related to the transportation of materials to and from site) have been identified and if the effect of these emissions on ambient air pollutant concentrations have been understood (Arup, 2012). For example, for the London Underground, a full assessment of its carbon footprint has to be carried out as part of their policy. Emission sources of indirect carbon emissions that arise from transport-related activities, such as rail replacement, should also be assessed (Mayor of London, 2009).

Ozone depleters: This indicator explores whether any ozone depleting substances are proposed for use in the construction or operation of the project. This is to ensure that the construction is not involved in destroying the ozone layer (Arup, 2012). However, it is suggested that underground construction (accepting mining works) does not directly affect the ozone layer and looking through literature, no evidence of underground construction impact on ozone layer has been found. Therefore, this indicator could be excluded. That is not to say that there will be no indirect impacts through materials processes used – in which case this would be considered in the materials indicators.

4.4.1.2 Social pillar

Table 4.2 demonstrates the social pillar of the SPeAR® framework and provides comments on their relevance to UUS use. This includes the modified narratives for each indicator. The rational for including or excluding each indicator is described below.

Table 4.2: SPeAR® social pillar

Core indicators	Sub-indicators	Comments
Community facilities	Recreation	Appropriate
	Education	Appropriate
	Healthcare	Appropriate
	Retail	Appropriate
Culture	Respecting socio-cultural identity	Inappropriate
	Cultural and religious facilities	Appropriate
	Use of environment	Appropriate
	Intergenerational and gender practices	Inappropriate
	Archaeology and local heritage	Appropriate
	Art	Appropriate

Form and space	Density, Height, scale and massing	Appropriate with modification/ Density, depth, scale and massing
	Public, private and communal space	Appropriate
	Landscape, townscape and visual impact	Inappropriate
	Security	Appropriate
	Connectivity	Appropriate
	Microclimatic	Inappropriate
Stakeholder engagement	Identification and analysis	Appropriate
	Engagement process and feedback	Appropriate
	Integrating stakeholders' comments	Appropriate
Health and wellbeing	Access to green space	Appropriate
	Community cohesion	Appropriate
	Institutions and social networks	Appropriate
	Indoor environment	Appropriate
	Social vibrancy	Appropriate
Transport	Public transport infrastructure	Appropriate
	Pedestrian design and facilities	Appropriate
	Cycle design and facilities	Appropriate
	Waterways	Appropriate
	Freight traffic	Appropriate
	Low emission vehicles	Appropriate
	Private vehicle use	Appropriate
	Air travel	Appropriate

1. Community facilities

Recreation: UUS may help to provide recreational facilities in some circumstances. For example, the extensive downtown underground pedestrian connections in both Montreal and Toronto were initiated as a part of major redevelopment projects mainly to avoid extreme weather conditions (e.g. snow) (Boivin, 1991; Parriaux, 2006). Furthermore, Carmody and Sterling (1993) provided other examples of modern recreational facilities constructed underground including sport facilities and community centres. An example is an underground swimming pool in Itäkeskus in Helsinki, Finland (Vähäaho, 2011 and 2014). Therefore, this indicator could be considered to improve an underground project.

Education: Additions to existing aboveground, commercial or institutional buildings may be placed underground to retain proximity to existing facilities and to preserve the aesthetic of open existing open spaces. Carmody and Sterling (1993) describe that educational buildings are an important class of underground structure and they are usually shallow cut-and-cover structures to facilitate fire exit requirements. Library extensions are also an example of this type of facility. The underground school facility in Arnhem, the Netherlands is an example (Admiraal, 2006). An underground project could be enhanced by inclusion of this indicator.

Healthcare: There are medical facilities and emergency response facilities located underground in cities around the world. For example, during the Second World War, Germany and Britain both used underground hospitals (Carmody and Sterling, 1993). Above ground healthcare is essential, as underground care might not be desirable for some people due to psychological effects, for example, Carmody and Sterling (1993) observe that patients in windowless hospitals are more likely to develop depression, even though the building may have adequate artificial lighting, mechanical lighting and ventilation (Carmody and Sterling, 1993; Roberts et al., 2016). Though, the space below ground could be useful for underground emergency departments or operating theatres (Carmody and Sterling, 1993). This indicator helps decision-makers to improve a project by providing a better access to healthcare facilities.

Retail: Similar to the recreational indicator, underground shopping centres are a good use of the space below ground. A good example is Les Promenades de la Cathedrale in downtown Montreal (Durmisevic, 1999). As well as this, the new Bullring retail shopping centre in Birmingham, UK is linked through underground shops (Hunt et al., 2016). This indicator reflects the opportunities that exist for enhancing retail potential through wider use of UUS.

2. Culture

Respecting socio-cultural identity: This indicator is about how the UUS project contributes to the reflection of cultural and social background. This helps identify considerations for how UUS may affect upon local socio-cultural identities. For a project to be located underground, it could be improved by, for example, placing a mosque or church in the facility and respect other cultures. This indicator is excluded since the next indicator *Cultural and religious facilities* covers the same idea with respect to UUS. An underground project, which includes cultural and religious facilities, could be considered as contributing to respecting to socio-cultural identity.

Cultural and religious facilities: Linking with the above indicator, UUS has significant potential to be used for religious purposes. The special characteristics of a dark, silent and somewhat forbidding environment can provide a separation from the normal world and opportunity for spiritual reflection (Carmody and Sterling, 1993) and above all the lack of need for a natural day lighting source makes underground space an appropriate choice. Modern-day underground churches do exist, for example the Temppeliaukio church in Helsinki, Finland, is built completely underground in solid rock (Vähäaho, 2011). Therefore, an underground facility could be enriched with including this indicator.

Use of environment: This indicator measures if the existing natural or hand-made features in the local environment have been featured into the project (e.g. topography) (Arup, 2012). For example, Li et al., (2013b) lists a series of criteria such as soil and land use type and topography for potential development of UUS. The latter can improve an underground facility by using the existing environment – this was certainly the case in the Helsinki examples stated previously where rock faces are exposed within the structures (e.g. swimming pool and church).

Intergenerational and gender practices: This indicator mainly measures the impact of different gender practices or generations (Arup, 2012) on UUS use. In the past, females were banned from taking part in underground projects such as mining, however nowadays this type of restriction no longer applies. Furthermore, the United Nations has agreed on the new Sustainable Development Goals (United Nations, 2015), in which of the 17 goals, one is achieving gender equality. Also, reviewing regulations such as Crossrail or HSE with respect to UUS, has shown that UUS does not bring any constraint for different gender or generations, hence, this could be excluded.

Archaeology and local heritage: This indicator is tied to concerns such as if there are archaeological issues on the site or if there is historic, heritage building on site and if 'yes' how they are assessed, protected and enhanced as part of the project (Arup, 2012). Underground constructions may lead to the destruction of nearby or underlying heritage, not least when tunnelling (Wang et al., 2014). And certainly, it has been the case that when underground construction has taken place many significant archaeological sites has been uncovered (e.g. medieval findings in Farringdon Station, London, UK) (Smith, 2016) and necessarily preserved for future generations. Therefore, this indicator is included to ensure a project is not disturbing local heritages.

Art: Use of UUS has the potential to provide additional space for art preservation and therefore improving cultural aspects of a community, for example there are many art works on the walls in Moscow underground stations (Labbé, 2016). Furthermore, Hoeven and Juchnevic (2016) discuss the importance of experience in the design of an urban underground space. The authors argue that going underground is actually an exciting experience with respect to art. For example, for an underground station, the design can improve or weaken that experience. The authors suggest that art is just an addition to underground stations, which helps to sooth the negative feelings, or perceptions that concerns users when being in an underground space. Birmingham New Street Station (2010–2015) redevelopment is such an example (Hoeven and Juchnevic, 2016). Therefore, this indicator is relevant to a case of UUS and can improve UUS construction.

3. Form and space

Density, height, scale and massing: The original SPeAR® indicator is closely related to buildings where it is possible to have high density and mass with integration of much higher buildings in the city centre (Arup, 2012), which leads to the feeling of a crowded city. However, the modified indicator considers the *"density, depth, scales and massing"*. Though dealing with UUS construction, depth of excavation into the ground plays an important role and will affect ground movements both surface and sub-surface. As an example, Rogers (2009) discusses the impact of three different cases of medium, medium depth and shallow underground construction on above ground structures. For a facility located underground considering this indicator aids sustainability of the project.

Public, private and communal space: This indicator aims to make sure all three different categories of public, private and communal facilities are considered within the project (Arup, 2012). This is applicable to the extensive likely future use (and potential) of UUS, whereby using UUS more effectively can be a facilitator in all three aspects. Inclusion of this indicator can help to enhance an underground project.

Landscape, townscape and visual impact: This indicator simply measures how well the project will help to improve our landscape and visual impact. This is linked to whether landscape has been a consideration of the project and if the open areas have been considered in the design of the project. Alternatively, whether the existing landscape has been incorporated in the project design (Arup, 2012). Landscape is part of an environment, which is a place of our current actions, and we can interact with it now. In fact, environment and nature are the main contexts of landscape architecture. In micro scale, landscape represents itself as the architecture of a building and in macro scale, as a city and urban designing (Motealleh et al., 2015). Therefore, this indicator is building related and belongs to the surface which will be ultimately excluded. Alternatively locating a facility underground it has the benefit of improving the landscape, townscape and visual impact of the area above ground as it has been considered in projects such as Madrid Calle 30 – M30 motorway project in Spain and the Boston Artery project in the USA, which aimed to reduce the impact of vehicular traffic and provide access to new green space above ground (Hunt et al., 2016). However, these considerations has already been given under indicators such as 'connectivity' or 'access to green space'.

Security: UUS and related infrastructures tend to have limited access points and there is therefore an increased risk of public attacks or sabotage in underground channels and tunnels (Bobylev, 2009) (e.g. multi-utility tunnels that house combined utility infrastructures or underground MRT systems could be a target systems). Such facilities need to be secured against human intervention or even acts of terrorism. For instance, Bobylev (2009) states that one of the major problems associated with long pedestrian crossing tunnels are criminal attraction. In addition, this has had implications for the subsequent removal of a number of pedestrian underpasses in Birmingham, UK (Jefferson et al., 2007). Currently in the UK, CCTVs are in operation, but still there is a debate on the location and effectiveness of these cameras (Bobylev, 2009). Considering this indicator will help to improve an underground project in terms of security.

Connectivity: UUS use can provide faster and quicker connections between different areas of a city, either in city centres where there is not available space above ground for transportation or where there is no opportunity available due to geotechnical reasons. For example, the "Big Dig" project in Boston relocated Boston's central transport artery underground resulting in a corridor of new, publicly accessible open space above ground (National Research Council, 2013). Therefore, an underground project could be enhanced by considering and improving connectivity.

Microclimatic: This indicator considers if attention has been given to how design proposals might affect the microclimate, such as contemplations with respect to how the project creates a desirable microclimatic for the users, or how the project could influence the existing microclimatic (Arup, 2012). This includes air quality concerns which cover the desirable environment for users of underground, and have already been considered and discussed in Section 4.4.1.1 in 'air quality' indicator. Its other aspects can be how the project affects the microclimate of above ground, including solar access and shade, heat island effect and the effect of wind which are covered under the indicator 'carbon pricing' (Section 4.4.1.3). Hence, the indicator microclimatic could be excluded.

4. Stakeholder engagement

Identification and analysis: This indicator mainly refers to identification of all stakeholders (i.e. those that plan for and use UUS) which is necessary, regardless of whether the project is above ground or underground project. Their identification and engagement from the outset of a project is vitally important to ensure initial buy-in and smooth running of the project. According to Edgerton (2008), the greater part of heavy civil construction is for governmental agencies, and the public is the ultimate beneficiary of these projects, standing to gain the most benefit from them and at the same time, they are the ultimate risk takers. However, the author also mentions that design engineers, construction manager, owner agency and contractor would be involved as well (Edgerton, 2008).

Engagement process and feedback: With respect to UUS as with any other construction projects, it is important for different stakeholders to be engaged and involved to avoid further conflict (Edgerton, 2008). The stakeholder relationship from the beginning of a project evolving through all of its phases maybe the most crucial yet most fragile part of the entire project delivery process (Edgerton, 2008).

Integrating stakeholder comments: Similar to other construction projects, feedback and comments obtained from engagement of stakeholders should be considered to make sure best practice is done and all stakeholders are satisfied. This would lead to betterment of a project (Edgerton, 2008).

5. Health and wellbeing

Access to green space: A recent study by Commission of Architecture and the Built Environment (CABE, 2010), states, "*access to decent green space, alongside housing, health and education, is a basic requirement for a good quality of life*". Including this indicator will help planners or decision-makers to improve an underground project by providing a better access to surrounding green spaces, such as parks. Projects such as Madrid Calle 30 – M30 motorway project in Spain and the Boston Artery project in the USA are some of the recent examples (Hunt et al., 2016).

Community cohesion: This indicator determines the integration between different groups and communities. It assesses whether the project can meet the needs of existing communities and potential newcomers to avoid tension, for example competition over housing and jobs. In this case the indicator could be used to assess the broader implications for how ultimately construction of underground facilities (as part of a broader underground city), contributes toward bringing communities together. Hence, this indicator's inclusion could help to improve an underground project.

Institutions and social networks: This indicator measures the linkage between communities and institutions. For instance, loss of mobile network connectivity may not allow the modern day social interactions to take place whether by texting, or through Instagram, Flicker, Twitter, and Facebook - this is particularly true when you lose Wi-Fi signals in UUS. This is the reasoning behind why recently Wi-Fi has become available in London Tube, and now people are able to send a text or make a call (Charlton, 2015). Any underground project could be improved by considering this important element which will improve the connection between social networks – a necessary part of modern day living

Indoor environment: Considering this element, which underlines architectural technologies in lighting and physical design, enhances underground space's attractiveness. This has been given credit by architects around the world in recent years. It has been claimed that interior space improvement quality can increase public acceptance of using underground space (Von Meijenfeldt and Geluk, 2003). Therefore, this indicator is considered appropriate and extremely important for UUS.

Social vibrancy: This indicator refers to bringing different groups of society together. For example, if the project provides appropriate spaces for people to meet and socialise and if the project ensures that all members of community can benefit from the opportunities for social activity (Arup, 2012). An underground facility could be improved by considering social vibrancy as an aspect during deign stages.

6. Transport

Public transport infrastructure: Underground space has been widely used for the purpose of transportation around the world and transportation is a widely used indicator to assess the sustainability of underground space (Bobylev, 2009 and 2016). Allowing for inclusion of this indicator would help to enhance an underground project by providing a better transport system.

Pedestrian design and facilities: Pedestrians access (e.g. underpasses and interconnections between transport modes) has been placed underground for hundreds of years. The extensive downtown underground pedestrian connections in Montreal and Toronto were initiated as part of a major redevelopment projects (Bélanger, 2007) and such adoption, perhaps not on the same scale, can be seen in many major urban centres. This indicator helps to bring more sustainable opportunities to an UUS construction project.

Cycle design and facilities: Underground space has not been used for cycle routes. However recently there was an award-winning plan to convert disused London Underground routes into subterranean cycle ways and pedestrian routes to making London safer and less congested

(Peyer, 2015). Therefore, there seems to be no reason why underground cycling could not exist. This indicator can improve an underground project by adding this feature.

Waterways: This indicator is about whether the project is located near waterways and if the waterways have been used for freight journeys where possible (Arup, 2012). Considering this indicator can improve an underground facility's sustainability in terms of transport.

Freight traffic (Logistics). This indicator is about the freight traffic journeys by rail or water versus the road transport and if low emission vehicles have been considered for freight transport (Arup, 2012). For example, as part of Crossrail's sustainability strategy, for tunnelling operations have been planned to maximise the use of non-road transport for the removal of excavated material. In addition, it has been stated that 80% of excavated material has been transported by water or rail leading decreasing lorry journeys on the streets (Crossrail, 2016).

Low emission vehicles: Air quality is one of the concerns with any underground environments and therefore mandatory controls regarding use of high emissions vehicles in UUS is required (Demir, 2015). Generally, not many vehicles are used below ground except the one used for construction of major tunnels and are specifically built for this purpose. For example, Crossrail is committed to reducing particulate emissions from construction machinery as part of its environmental management requirements. Moreover, they believe that the use of these cleaner engines will contribute to improve air quality in London, especially for communities around Crossrail's sites (Crossrail, 2016).

Private vehicle use: Low emission vehicles used underground for the purpose of construction should be actively encouraged for example by prioritise parking or if the alternative fuel provided by the project is linked to a wider network (Arup, 2012). These can be related to a log of the vehicle use showing the details of any emissions controls being used (Crossrail, 2016). For example, for underground tunnels, any vehicle, planned to be used below surface, needs to be based on the air quality regulations and specifically convey the restrictions allocated. An example is Tyne Tunnel, North East England which the air quality of tunnel was carefully investigated (de Wit and Fay, 2003).

Air travel: This indicator aims to determine the impact of the project on air travel. Since UUS facilities do not affect air travel systems directly, this indicator could be deemed irrelevant. However, that is not to say that use of UUS cannot be a facilitator for air travel, exampled most recently by the Terminal 5 Heathrow Express tunnels (Shanghavi et al., 2008). An underground facility could be improved by considering opportunities through easier air travel. This indicator would need to be considered on a case-by-case basis.

4.4.1.3 Economic Pillar

Indicators in economic category are shown in Table 4.3 and comments are provided on their relevance to UUS use further below.

<u>*Table 4.3: SPeAR® economic pillar*</u>

Core indicators	**Sub-indicators**	**Comments**
Facilities management	Usability	Appropriate
	Appropriate technologies	Appropriate
	Whole-life flexibility	Appropriate
	Operation and maintenance	Appropriate
Governance and reporting	Monitoring and evaluation	Appropriate
	Information disclosure and reporting	Appropriate
	Strategy	Appropriate
	Risk management	Appropriate
	Donations to voluntary and community organisations	Appropriate
Economic effect	Value for money	Appropriate
	Distortions to local economy	Appropriate
	Vitality and regeneration	Appropriate
	Carbon pricing	Appropriate
Employment and skills	Labour standards	Appropriate
	Employment creation	Inappropriate
	Employment creation in construction	Appropriate
	Employment creation in operation	Appropriate
	Training	Appropriate
	Access to finance	Appropriate
	Social mobility	Appropriate
Site selection	Site location	Appropriate
	Planning intent	Appropriate
	Diversity/mixed use	Appropriate
Procurement	Local sourcing	Appropriate
	Global sourcing	Appropriate
	Procurement strategy	Appropriate
Equality	Affordability	Appropriate
	Designing for equality	Appropriate
	Impacts and benefits	Appropriate
	Land tenure	Appropriate
	Displacement	Appropriate

1. Facilities management

Usability: In the design of any UUS facility, it is essential to consider the maximum functionality and usability of the infrastructures being adopted therein. For example, to check whether the project has been designed taking into consideration the future occupier or an operational and maintenance manual been prepared to support further use (Arup, 2012). This has significant impacts in terms of how the facility will ultimately be accepted or used.

Appropriate technologies: This indicator highlights whether an appropriate technology has been used for the project with respect to the present location and conditions (Arup, 2012). For example, in developing countries greater use might be made of manual labour than in the developed countries, where far more complex and expensive machinery is likely to be used. Therefore, regardless of underground or above underground construction an indicator that refers to best available technique (BAT) is certainly applicable.

Whole-life flexibility: This indicator relates to the flexibility of a project over its lifetime. For example, if the project is adaptable to future changes (e.g. environmental, social and economic conditions) (Arup, 2012). Examples of such changes are climate change or consumer preferences, which might change over time. Therefore, this indicator should be considered to make sure the facility is flexible enough to be maintained in the future (National Research Council, 2013).

Operation and maintenance: This indicator demonstrates the two stages of operation and maintenance involved in the life of any infrastructure located below ground and the level of difficulties to manage those facilities with respect to operation and maintenance. These aspects must be considered during the earliest possible opportunities in the design, for example, Hunt et al., (2014) compare two methods of shallow utility placement via cut and cover versus multi utility tunnels (MUT), and state that for the latter, repair and maintenance could be done without the necessity for excavation. This implies that the structure brings with it many long-term advantages in this area (for example cost and avoiding disruptions). This indicator allows these benefits to be considered at early stages of an underground facility development.

2. Governance and reporting

Monitoring and evaluation: This indicator reflects the need for a monitoring plan to be used to compare actual performance with designed performance, and to evaluate continued performance and maintenance (Arup, 2012). For example, in terms of utility placement, it might be considered as evaluating the 'reported' additional benefits with actual performance – in other words how much was maintenance facilitated by such an approach and how much time / money was saved compared to other alternative options.

Information disclosure and reporting: This mainly refers to the confidentiality of data and permitted materials to third parties or public domain (Arup, 2012). This does not appear to be a direct influence of UUS. However, every project, which uses UUS requires much data provisioning – for example, in terms of borehole information that allows for soil properties and geological features to be better understood. These data if disclosed and reported in a standardised way will help planners to understand how UUS is being used and potentially how it could be used as part of an overarching holistic planning (U.S. National Committee on Tunnelling Technology, 1976).

Strategy: This indicator mainly explains the long-term plans for the facility. This includes consideration of the impact of all stages (construction through to end-use) involved in the life of the UUS facility including decommissioning at the end of its life (Arup, 2012). This is applicable for both above ground and underground construction. Some might suggest for underground construction it is more important because what is left behind is not readily seen and can produce future hazards.

Risk management: For UUS projects the risks are always going to be much larger than for similar 'above ground' projects (Reily, 2005; Parker and Reily, 2008). An important question to ask in this respect, during the early phases of such a project, is: "Who should take responsibility and thus who should burden the risks?" Therefore, this emphasises that for UUS projects there is a strong need to have an advanced plan for dealing with potential future risks. This is not only during the construction phase but also during the operation phase (Reily, 2005; Parker and Reily, 2008). Therefore, this indicator's inclusion is necessary.

Donations to voluntary and community organisations: This indicator is mainly for organisations to show their corporate social responsibility. In addition, it investigates if contributions have been made to relevant voluntary community and organisations (Arup, 2012). This is equally applicable for above or below ground projects.

3. Economic effect

Value for money: Despite the obvious advancements in technology and construction methods (e.g. MUTs), UUS developments are often considered to incur higher initial costs compared with those developments located on the surface and this issue can give rise to doubts relating to the effectiveness of investing necessary public funds (ITA, 1985). It is estimated that construction costs of underground facilities are 2 to 4 times greater than for similar ones on the surface (Zhao and Cao, 2011). This is a significant drawback where short-term economic benefits are considered. However, the project may deliver direct benefits in terms of maintenance costs saved or long-term benefits and these are not always considered in conventional costing models. This indicator allows this to happen by bringing these benefits to the attention of decision-makers.

Distortions to local economy: This indicator explains the influence of the UUS project on its surrounding area and its potential negative impacts for the local economy. Key issues to consider for example, include competition for local jobs/services and disruptions to utilities and alternatively considers if the UUS facilities' influence on local economy has been determined (Arup, 2012). This indicator helps to improve the economic sustainability of an underground project in these terms.

Vitality and regeneration: This indicator explains the UUS projects contribution to a thriving local economy (Arup, 2012). For example, UUS infrastructures could bring an opportunity to attract more people to the area through improved transportation networks, and access to new or improved recreation and retail amenities. In addition, locating certain aspects of the urban area below ground can be an enabler for urban regeneration potential above ground.

Carbon pricing: This indicator covers the UUS impact on air quality concerns, specifically carbon emissions and their economic impact. Authors such as Yang et al., (2014) argue that there is still a lack of systematic theoretical research on this topic. The term "carbon pricing" refers to putting a price on carbon (there are different ways governments can take to price carbon. It is started by capturing what are known as the external costs of carbon emissions (World Bank, 2015b). For example, the release of carbon dioxide will affect climate change therefore the cost of damage to climate change, such as weather conditions (not least rainfall, flood risk and temperature rises) needs to be considered. Hence, for any UUS facilities the amount of carbon emissions created needs to be measured and mitigated for, otherwise carbon pricing will be considered.

4. Employment and skills

Labour standards: As a part of good practice, this indicator ensures that engaged organisation(s) place a legal requirement to ensure that workers' rights and conditions in the work place (either during construction or after) are considered, and meet certain levels of comfort and safety (Arup, 2012). This particularly applies to UUS working conditions, depending on the use (during construction, operation and maintenance), as it can often be more inhospitable and dangerous than those found above the ground.

Employment creation: This indicator refers to the role of the UUS project in the creation of job opportunities, both during construction and operation. It is about whether the project prioritises labour-based rather than technology-based activities during construction, operation and maintenance and how employment opportunities will be sustained once the project is finished. However, in the SPeAR® software it explains that there is a possibility for this indicator to be replaced by two indicators of "*Employment creation in construction" and Employment creation in operation"* (Arup, 2012). This suggestion was adopted in this research. Therefore, the indicator "employment creation" has been omitted.

Employment creation in construction: This indicator is a representation of the opportunities that a project may bring in terms of employment creation during the construction phase. For instance, considerations include whether the project is prioritised as labour-based rather than technology-based during construction (Arup, 2012). Similarly, for UUS construction, there is an opportunity for a number of jobs to be created, therefore, this indicator is applicable.

Employment creation in operation: This indicator investigates whether local people are given the opportunity to benefit from job creation (Arup, 2012). For example, for the new project of Crossrail, it is claimed that 990 full-time jobs in operation and maintenance will be created (Crossrail, 2015). However, there might be some indirect jobs created as a result of such a project, for example employment at new restaurants that serve the new workforce.

Training: This indicator explores the adequacy of training for all UUS workers. There is a need for training at all levels, e.g. apprenticeships through to senior managerial training (Arup, 2012). There is no difference between underground or above ground projects and this indicator could be applied to UUS projects.

Access to finance: Construction is one of the largest sectors of the economic activity (Blackburn et al., 2012) and the underground economy is a pervasive feature of countries throughout the world (Gorshkov and Epifanov, 2016). For any project (above or below ground) it is important to have a clear understanding of the sourcing of the budget, how it is provided and whether enough funds are available. For example, Gorshkov and Epifanov (2016) discuss the important role of a competent organisation in the success of an investment project. The author proposes a composition of the project financing participants, including buyers, bank and major shareholders, taking into consideration their responsibilities for a UUS project. Hence the inclusion of this indicator is necessary.

Social mobility: This indicator evaluates whether opportunities are created for people at a range of skill levels and types (Arup, 2012), and if the project helps to make a shift in people's social status during its operational life. For example, a new underground station can bring new economic opportunities for a local community by connecting it to bigger markets. Such a project can also enhance social mobility through providing access to education, health and leisure, which are fundamental elements for intergenerational social mobility and community life stage improvement (Dempsey et al, 2011; Miciukiewicz and Vigar, 2012).

5. Site selection

Site location: This indicator reflects the preliminary stage of the design of a project and the importance of choosing the right location. This is of primary importance for any UUS project in order to avoid any disturbance to other existing surface and subsurface developments, ongoing projects. In addition, it includes cognisance of whether the site (and UUS project) inhibits / prohibits future developments. This is an important indicator since it includes geology, groundwater, avoiding faults and other areas of ground instability, as well as avoiding existing structures and services (Hoeven and Juchnevic, 2015).

Planning intent: Planning intent is relevant to land designations associated with the project locations (e.g. built heritage) and if the proposed project complies with local/regional/national planning for the site (Arup, 2012). Which applies to UUS as well.

Diversity /mixed use: This indicator demonstrates how effective land use planning has been taken into account, to achieve an optimised planning decision. This indicator determines if there is a variety of services and facilities provided by the project with access to these facilities for all local residents (Arup, 2012). This indicator could enhance an underground facility by providing a range of facilities.

6. Procurement

Local sourcing: This indicator is relevant to the consideration of local availability of materials, goods and skills during different stages of a project and if there is an opportunity to prioritise local suppliers through procurement as well as if the project can provide opportunity or support for community suppliers (Arup, 2012). This is applicable to any project, placed underground or above ground.

Global sourcing: This indicator provides identification of whether there is a policy for sustainable procurement and global sourcing. This includes whether all sustainability issues associated with global sourcing have been appropriately considered (Arup, 2012). This is similar to the former indicator in the fact that there is no discernible difference between underground or above ground.

Procurement strategy: This indicator primarily concerns the supply chain, and how it is engaged throughout the project. For UUS facilities, this considers supply management, as well as risk and costs minimisation through; early involvement of a geotechnical advisor, site investigation, value engineering during the design process, well-managed construction and appropriate procurement contracts (Chow et al., 2002).

7. Equality

Affordability: This indicator explains if the facility is affordable for everyone. In other words, people from different financial backgrounds are able to use or gain benefit from it. Affordability reflects the social level that the project is aimed at, e.g. a toll tunnel in UUS with a high price may dissuade many drivers from using it. The Mersey tunnels provides an example for the UK where such an issue has been raised in the past (BBC News, 2014).

Designing for equality: It is important to consider whether the constructed facility includes access for all, including people with disabilities. For example, Crossrail has become one of the latest organisation to demonstrate commitment to disability equality (Crossrail, 2016).

Impacts and benefits: The indicator measures the social, economic and environmental impact that the project has on the neighbouring community. In addition, whether strategies have been identified to mitigate negative impacts and makes sure there is a process to implement these strategies (Arup, 2012). For UUS the short-term impacts are likely to be fairly high but these need to be set against long-term benefits such as wealth creation, job creation, improved connectivity and accessibility of space (Godard, 2004).

Land tenure: This indicator is related to land ownership rights. It determines how individuals and groups, access and use land and what their rights are to hold land. For example, ITA-WG4 (2000) discusses who owns the subsurface and mentions the legal framework related to ownership of subsurface space is regarded as a problem. Considering this indicator helps to improve sustainability of underground project in terms of economic aspect and land ownership rights.

Displacement: Displacement in a UUS context is about how the project will affect existing communities (Arup, 2012). For example, will people be relocated, will communities be split. This is applicable to UUS as well as above ground projects.

4.4.2 Materiality details for the modified indicators

The SPeAR® indicators have been reviewed in the previous section and relevant justification of how an underground facility/project can relate with the indicators have been presented. However, some indicators have been found irrelevant to underground space, which have been ultimately removed or modified. Summary of the materiality review of excluded/modified and included indicators is presented in Tables 4.4 and 4.5 respectively.

Table 4.4: Modifications made to SPeAR®

Pillar	Core indicator	Sub-indicator	Modification	Materiality review
	Indicator			
Environment	Biodiversity	Habitat connectivity	Excluded	The concept has been covered in other indicators within its category. However generally it is an above ground related indicator.
Environment	Waste	Composting	Excluded	Composting is widely used as a recycling innovation for organic wastes. Composting, the recycling of organic wastes such as vegetation and food waste, diminishes the amount of waste going to landfill and is hence a quickly growing sector (HSE, 2016). However, underground space facilities do not bring any opportunity for this purpose.
Environment	Climate change	Carbon sequestration	Excluded	No evidence found of an underground facility improving carbon sequestration.
Environment	Air quality	Ozone depleters	Excluded	Lewis et al., (2015) discuss the construction activities that lead to ozone depletion and they suggest ways to tackle this. However, ozone-depleting substances are only the result of above ground constructions and underground construction will not impact this.
Social	Culture	Respecting socio-cultural identity	Excluded	This concept is covered under "cultural and religious facilities" indicator. Moreover, it can be seen that excluding this indicator will not make any financial, social and environmental risks as it has been already covered.

	Culture	Intergenerational and gender practices	Excluded	Use of underground space does not bring any constraints for different genders or generations.
	Form and space	Density, height, scale and massing	Modified to "Density, depth, scale and massing"	With underground construction, it is "depth" which is considered rather than "height", therefore this indicator has been modified to "density, depth, scale and massing". Since height is not involved in underground construction, i.e. a project goes deep down rather than high upwards, and height is considered for surface projects where buildings go upward.
	Form and space	Landscape, townscape and visual impact	Excluded	This indicator is relevant to above ground and surface projects where there are concerns with aesthetic views and landscape. The extent that an underground facility can impact landscape is covered in indicators such as "connectivity" and "access to green space".
	Form and space	Microclimatic	Excluded	The measurement of microclimatic of UUS has been covered in 'Air quality' indicator, and the impact of UUS on microclimatic of above ground have been covered in 'carbon pricing'.
Economic	Employment and skills	Employment creation	Excluded	This indicator was considered into two separate indicators of "employment creation in construction" and "employment creation in operation".

Table 4.5: USPeAR Indicators (and sub-indicators)

Environmental							
Soil and Land	**Biodiversity**	**Waste**	**Materials**	**Water**	**Energy demand**	**Climate change**	**Air quality**
• Contaminated land • Soil quality • Drainage systems	• Protected species and habitats • Conserving and improving local biodiversity	• Construction waste management plan • Waste in operation • Hazardous/special waste • Designing out waste	• Materials efficiency in design • Use of recycled or reused materials • Environmental and sustainability impacts of material • Healthy materials	• Water pollution • Water resources • Wastewater treatment and disposal • Water monitoring • Water supply • Construction	• Energy supply • Energy conservation and efficiency • Energy monitoring • Daylighting	• Carbon managemen t plan • Social impact of climate change • Physical impact of climate change • Economics of climate change	• Ambient air quality • Direct emissions • Indirect emissions

Social					
Community facilities	**Culture**	**Form and space**	**Stakeholder engagement**	**Health & wellbeing**	**Transport**

• Recreation • Education • Healthcare • Retail	• Cultural and religious facilities • Use of environment • Archaeology and local heritage • Art	• Density, depth, scale and massing • Public, private and communal space • Security • Connectivity	• Identification and analysis • Engagement process and feedback • Integrating stakeholders comments	• Access to green space • Community cohesion • Institutions and social networks • Indoor environment • Social vibrancy	• Public transport infrastructure • Pedestrian design and facilities • Cycle design and facilities • Waterways • Freight traffic • Low emission vehicles • Private vehicle use • Air travel

Economic						
Facilities management	**Governance & reporting**	**Economic effect**	**Employment & skills**	**Site selection**	**Procurement**	**Equality**
• Usability • Appropriate technologies • Whole-life flexibility • Operation and maintenance	• Monitoring and evaluation • Information disclosure and reporting • Strategy • Risk management • Donations to voluntary & community organisations	• Value for money • Distortions to local economy • Vitality and regeneration • Carbon pricing	• Labour standards • Employment creation in construction • Employment creation in operation • Training • Access to finance • Social mobility	• Site location • Planning intent • Diversity/ mixed use	• Local sourcing • Global sourcing • Procurement strategy	• Affordability • Designing for equality • Impacts and benefits • Land tenure • Displacement

4.5 Summary

This chapter has reviewed a range of sustainability assessment tools, including award-based tools such as (e.g. BREEAM, CEEQUAL and LEED) and continual improvement tools such as SPeAR®, Horizon and HalSTAR. The review indicated that they cannot be directly applied to UUS development projects. Either they are building-focused and put emphasis on the environmental pillar, such as CEEQUAL or BREEAM, or they include a large list of indicators which makes them over complicated, such as HalSTAR. Among the tools reviewed, SPeAR® is a continual improvement tool which includes 120 sub-indicators, under three pillars of sustainability, and is applicable to all projects. Hence, it has been selected as the most appropriate tool to make modifications in order to make it a holistic assessment tool for UUS.

According to the requirements set down in SPeAR® manual a materiality review has been carried out on the indicators, during which, some indicators were deemed irrelevant to UUS exploitation. The suggested changes have been reviewed, and approved by Mr. Peter Braithwaite. Overall, four indicators, from the environmental pillar, four indicators from the social pillar plus one indicator from the social pillar have been modified and one indicator from the economic pillar have been removed. The set of selected indicators for USPeAR now includes 21 core indicators and 88 sub-indicators (28, 30 and 30 indicators in social, environmental and economic pillar respectively) as shown in Table 4.6. The 88 selected indicators are used in Chapter 5 as part of the process for obtaining adequate indicator weightings.

Table 4.6: Summary of the modified/excluded indicators and included indicators

	Overall	Environment	Social	Economic
Number of indicators excluded/modified from SPeAR®	10	4	5 (1 is modified)	1
Number of indicators included	88	30	28	30

CHAPTER 5: QUESTIONNAIRE

In this chapter, it is shown how each of the 3 pillars, 21 core indicators and 88 sub-indicators are weighted. The need for developing a weighting for the framework was discussed in Section 2.7 and will not be discussed herein. However, the philosophy behind it is to help imply the significance and importance of respective sustainability criteria on UUS projects. In order to develop the weighting, a questionnaire was adopted, to provide an opportunity to get expert opinions on each of the identified indicators. This chapter outlines the adopted methodological process for adding a weighting to the newly developed USPeAR tool. The following dual steps were adopted:

- Questionnaire design (Section 5.1), allowing experts to rate the relevance of each indicator;
- Analysis of the questionnaire results obtained (Section 5.2).

5.1 Questionnaire Design

A questionnaire has been designed in the research study in order to estimate the weight value (level of importance) of each indicator. Each indicator is categorised under one of twenty-one core indicators that belong under a specific pillar, of which there are three. In short, a group of respondents are asked to rate the significance of each indicator in each of the pillars ultimately determining a hierarchy of relative importance to each other. These respondents are a panel of professionals selected from across the industry, in order to achieve as wide a perspective as possible.

In order to determine the way in which the questionnaire should be structured and the way in which data should be collected, literature has been reviewed (explained in Section 3.2.2) (Akbayrak, 2000; Kelley et al., 2003; Krishnaswamy et al., 2006; Eskandari Torbaghan et al., 2014). Therein it has been found that there are two common ways to gather data utilising a questionnaire:

1) Sampling and

2) Making use of experts

The former goes back to process of selecting a sample from population of interest so that the result achieved from these participants can be generalised to the population which they were selected from. Population in this situation means the group of people whom the researcher is doing research on (Krishnaswamy et al., 2006). Szolnoki and Hoffmann (2013) argue that for this method, any difference in results is greatly affected by sample size. For example, a study on willingness to pay for biodiversity, by Lindhjem and Navrud (2011), used a sample where 680 participants were involved (including face to face and online), but this was a small sample when compared to other studies, such as Blasius and Brandt (2010), who used 1300 participants, or a study by Szolnoki and Hoffmann (2013) who had 2000 respondents in their study.

The latter involves making the use of knowledge obtained from a diverse range of experts in the field, who are well versed in terms of experience, judgement and application including rules of thumb (Eskandari Torbaghan et al., 2015). Since a large number of respondents is required for first method, accordingly, this research has utilised expert opinion.

Participants were recruited via e-mail invitations sent to professionals from across the construction industry. In total, over one hundred experts in sustainability and underground space were contacted through email correspondence. Of these, 25 agreed to participate in the research. These included those working in civil engineering industry namely; construction companies, academic researchers, policy makers and government advisors. Gordon (1994) points out that most panels range from 15 to 35 respondents; however, there are studies with groups ranging from 7 (Chu and Hwang, 2008) to 115 experts (Grundy and Ghazi, 2009).

The adopted methodology is based on the work undertaken by Dickie and Howard (2000) for assessing environmental impacts of construction for BRE Centre for Sustainable Construction. Similar research approach was undertaken with the purpose of establishing a series of key issues of sustainable construction to be considered by the weighting exercise. In their research, two exercises were given to the respondents. Firstly, the indicators were assessed theme-by-theme, participants were able to allocate more points to issues that were considered more important to sustainability and less points to those that were considered less important to sustainability. In a second exercise, participants were asked to score the relative importance of the themes and sub-themes, thus ensuring a test of consistency and enabling evaluation of the overall importance of the themes relative to each other.

The questionnaire (see Appendix B for a sample of questionnaire) consisted of two main sections aimed at collecting data via two separate approaches:

I. Section 1: In this section questions were designed concerning the general impact of UUS on the three pillars of sustainability. The respondents were asked to allocate a total of 100 points between each pillar of sustainability, giving more points to issues that they considered more important. The aim of this part is to understand which pillar is of higher concern with respect to UUS (see Section 5.2.2 for results).

II. Section 2: For each of the single indicators respondents were asked to score their relative importance using a 5-point Likert Scale.

The scale was originally established by Likert (1932), which is by far the most widely used scale in survey research (Hartley, 2014). It includes asking respondents to demonstrate their levels of agreement with a statement. Normally, for a 5-point Likert scale, each scale could be labelled according to its agreement. For instance, level: 1 = strongly disagree, 2 = disagree, 3 = neither disagree nor agree, 4 = agree, and 5 = strongly agree. However, depending on what is being measured, the scale labels may be worded differently (Li, 2013). For the purpose of this research, since it involves the impact of underground space use on sustainability, the following 5–point Likert scale was selected:

- 1= very poor,
- 2= poor,
- 3= neutral,
- 4= good,
- 5= very good.

Responses with a high level of agreement in the “very good” group were considered as the most important criteria for UUS development. These were subsequently highlighted within all three pillars and the responses with the major level of agreement on "very poor" group are considered as the least important indicators regarding the impact of underground space on sustainability.

When filling out the questionnaire, the participants were encouraged to consider any UUS project that they had engaged with or came across. In addition, an introduction was given to a public library completed in Birmingham, UK in 2012, that provides an excellent recent UK example of how UUS can be used (Lomholt, 2014; Hunt et al., 2016).

5.2 Questionnaire Results

5.2.1 Experts

The 25 experts who participated in the questionnaire were subsequently grouped into following eight broad categories:

- ✓ Environmental activist
- ✓ Construction professionals – Client's representative
- ✓ Construction professionals – Contractor
- ✓ Construction professionals – Consultant
- ✓ Construction material producer and manufacturer
- ✓ Local authority, policy makers and planners

- ✓ Academics
- ✓ National policy makers and researchers

Figure 5.1 presents the number of experts in each group of expertise, which demonstrates that expert panel consist of two environmental activists, one client's representative, five contractors, four consultants, four construction material producers and manufacturers, three local authority and policy makers, five academics and lastly, one from national policy makers and researchers. The most interested group to participate in the study were constructions professionals (contractors) and academics and the least that showed interest were construction professionals-clients representative and national policy makers and researchers.

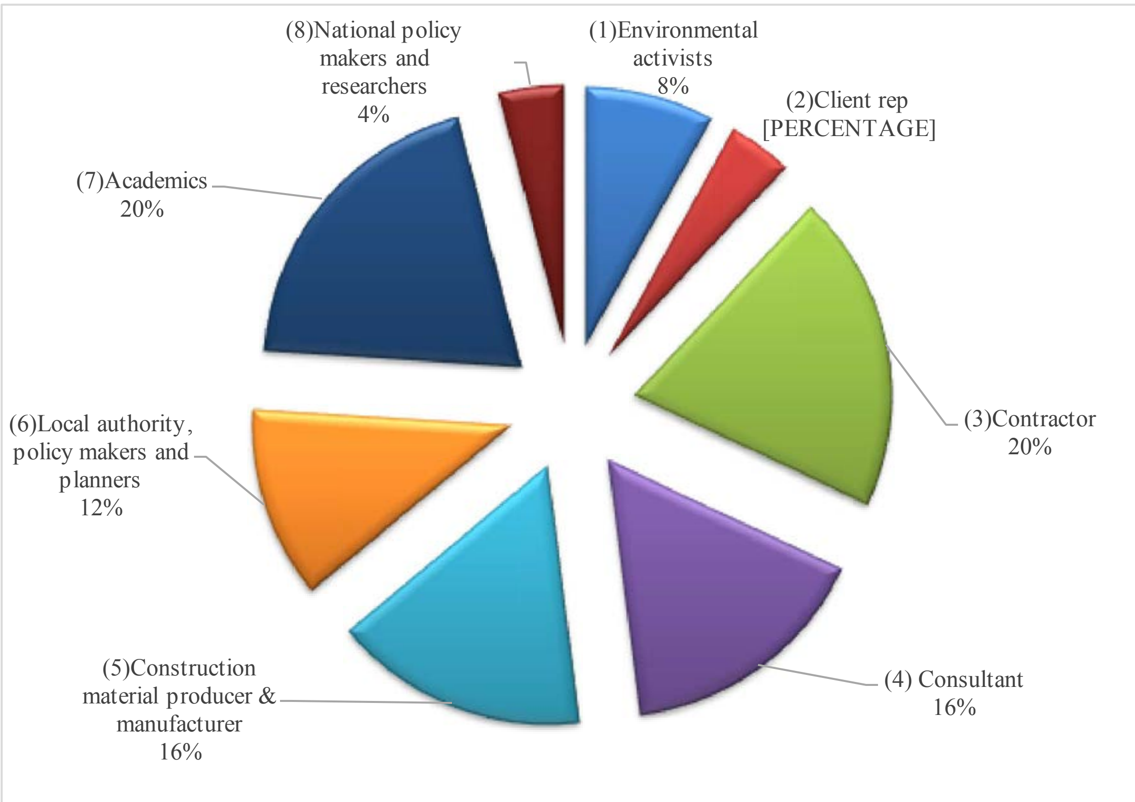


Figure 5.1:Experts' backgrounds

5.2.2 Limitations of the questionnaire and analysis of the first section of questionnaire

In the first part of the questionnaire, experts were asked to allocate 100 points between the three pillars of sustainability according to perceived importance.

Figure 5.2 is a graphic representation of the results. Interestingly, out of 25 participants who participated in the study, six experts agreed on the equal importance of three pillars of sustainability with respect to the underground space use. However, when averaging the numbers from all respondents it is notable that national policy makers and researcher agreed on the higher importance of the economic (60%), then environmental (15%) and the social pillar (25%). In contrast, the environmental activists have given higher scores to the social pillar (45%). In addition, the rest of the participants agreed to give more or less the same importance to each of the three pillars. This indicates the disagreements between two groups: environmental activists and national policy makers, and between these and the rest of the participants. The average result for three pillars of sustainability shows average scores of 35% for environment, 33% for society and 32% for economy.

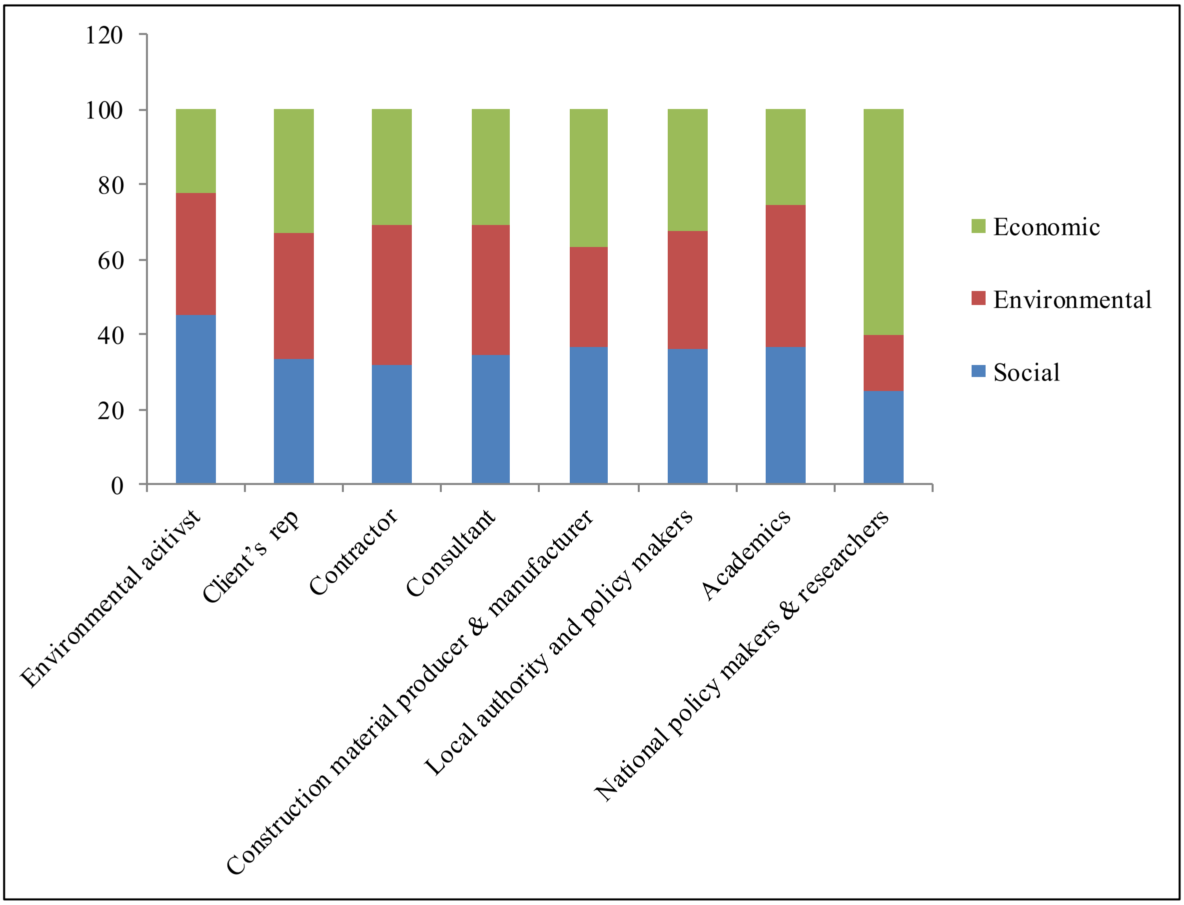


Figure 5.2: Results of the first section of the questionnaire

A major concern with qualitative methods, such as questionnaires, is inadequate validity and reliability (Bolarinwa, 2015). By designing a rigorous questionnaire and inviting participants who are active within field of construction and sustainability, the author attempted to involve participants who are well versed in their field of experience and who have wide-ranging view towards UUS. However, the research was limited due to the time required for data collection and the number of respondents forming the expert panel. Within this research and limited time, 25 individuals participated in the study. Unfortunately, in some categories there are only one or two participants such as 'national policy makers and researchers' and 'environmental activist'. This under-representation in some categories can result in not enough overall weight being assigned to those categories' concerns or interest.

In order to finally address the results obtained from the first part of questionnaire (i.e. rating UUS with respect to the three pillars of sustainability), these limitations had to be considered, alongside the fact highlighted by authors, such as Creswell (1994) and Zohrabi (2013), that any conclusion from questionnaire methodology should be drawn and validated by the other studies and theories. Furthermore, authors, such as Krosnick and Presser (2010), outline that a questionnaire is designed and based upon examination of the literature to confirm what has already been known. All in all, due to the aforementioned limitation of this research, i.e. the few participants, the author compared the results of the first part of questionnaire with the literature. The following section investigates this in detail.

5.2.2.1 Analysis of the first section of questionnaire

Through the definition of sustainability and sustainable development considered in this research (Chapter 2), it has been discussed that sustainable development is viewed as a roof (or umbrella) supported by three mutually reinforcing pillars of economy, social welfare and the environment. However, the necessity for growth and development and the need to protect and maintain the natural environment often leads to misperception and conflicting ideas. This is unfortunate given that environmental services underpin social and economic welfare and consequently sustainable development; the governance systems of all three pillars together form the core elements of sustainable development governance. In fact, the world's economies would fail without the services that ecosystems provide (UNEP, 2011). According to Giddings et al., (2002), it has been said that the core essence of sustainability could be economic, and without that, there will not be environment and ultimately society. Although, economy is the main element, but the result of the questionnaire show that all three pillars are attached together and it is difficult to decide which is more important. In addition, UNEP

(2011) discusses that if not all three pillars are equally strong then the roof may become unbalanced. A functioning sustainable development governance system requires that the governance structure for each pillar be equally strong and that all three be mutually supportive (UNEP, 2011). Hence, it is essential to integrate and reconcile the economic, social and environmental aspects within a holistic and balanced sustainable development framework. As well as this Strange and Bayley (2008) underpin that *"the core of sustainable development is the need to consider three pillars together, society, economy and the environment, no matter the concept, the basic idea remains the same: people, habitats and economic systems are interrelated."*

Hence, considering the three-pillar approach and combining with the results obtained from the questionnaire, promoting the idea of functioning sustainable development system requires that the governance structure for each pillar to be equally strong and that all three be mutually supportive. Therefore, for the purpose of this research the three pillars of sustainability have been assumed to be of equal importance, at 33.33% for all three pillars.

5.3 Reliability of the Questionnaire Results

The results of the questionnaires for each indicator of three pillars of sustainability are shown in Tables 5.1, 5.2 and 5.3. The results include the number of respondents to each indicator's relevance. However, an essential step before conducting further analysis on the questionnaire is testing the reliability and validity of the questionnaire (Al-Rubaee, 2012). Reliability tests are commonly utilised to provide an indication of the degree to which the measures used to evaluate the same thing are consistent (Saraph et al., 1989; Black, 1999; Antony et al., 2002; Ahmed, 2002; Eskandari Torbaghan et al., 2015). According to Boone and Boone (2012) in order to analyse Likert scale data, the adequate tests include the standard deviations for variability. For instance, Eskandari Torbaghan et al., (2015) used standard deviation to analyse the degree to which the involved participants were in agreement or disagreement on the utilised questionnaire. This was used to further analyse the potential rational behind verities in responses, where applicable. Therefore, for this research, a statistical analysis of the agreement between the experts' evaluations was conducted in order to inform further data analysis to identify potential limitations and to suggest improvements, such as engagements of other groups where a large disagreement is evident, in the process.

The results from the first and second sections of questionnaire will be explained and discussed below, in the light of results obtained by calculating the standard deviations of each set of responses obtained for each question.

5.3.1 Standard deviation

Tables 5.1, 5.2 and 5.3 also present the results and standard deviation (SD) for the three pillars.

The environmental pillar has an average standard deviation equal to 0.95, which is in between the other two pillars of social and economy, which are 1.01 and 0.89 respectively. This shows that between the indicators in the environmental pillar and the economic pillar there was a better agreement of respondents, compared to the social pillar.

Indicators with higher standard deviation in environmental pillar are:

1. Conserving and improving local biodiversity (SD = 1.15)

2. Three indicators in the waste category, namely i) construction waste management (SD = 1.24), ii) waste in operation (SD = 1.13), and iii) hazardous special waste (SD = 1.23).
3. There are two indicators of "water supply" (SD = 1.03) and "construction" in water category (SD = 1.08)

The disagreement between the indicators in the environmental pillar was predictable from the result of the first part of the questionnaire, which shows that all eight categories of respondents agreed on the environmental pillar, except the national policy makers and researcher (1 respondent), who believed the environmental pillar to be of least importance with respect to UUS. Also, it was found that academics gave more importance to environment, compared to the other group participants. There were 5 academics involved in the questionnaire, the highest number of respondents in one group. And specifically, investigating the details in some sub-indicators (Table 5.1) shows a high standard deviation for 'waste'. Whilst most of the respondents agreed on the high importance of the waste sub-indicators, there was one exception, the only one respondent from 'national policy makers and researchers', who considered 'construction waste management' and 'hazardous/special waste' as having a very poor impact on UUS. It could be comprehended that, compared to other sub-indicators within waste category, these two have the least importance not in fact underestimating the importance of waste.

In addition,

4. There are three indicators of 'soil quality', 'designing out waste', 'social impact of climate change', 'economics of climate change' and 'indirect emissions' with SD =1.

This indicates the equal number of agreement and disagreement between respondents with respect to these indicators.

However, the rest of the indicators have lower standard deviation, which is an indication of agreement between respondents with respect to those sub-indicators.

Table 5.1: Questionnaire results of environmental pillar and associated Standard Deviation (SD)

Core indicators	Sub-indicators	Very poor	Poor	Moderate	Good	Very good	SD
Soil and land	Contaminated land	0	2	3	14	6	0.84
	Soil quality	0	3	6	9	7	1
	Drainage systems	0	1	5	8	11	0.90
Biodiversity	Protected species and habitats	0	1	9	6	9	0.95
	Conserving and improving local biodiversity	0	5	8	4	8	1.15
Waste	Construction waste management	1	3	5	5	11	1.24
	Waste in operation	0	3	10	2	10	1.13
	Hazardous/special waste	1	4	8	4	8	1.23
	Designing out waste	0	2	9	6	8	1
Materials	Materials efficiency in design	0	1	4	11	9	0.83
	Use of recycled or reused materials	0	3	9	7	6	0.99
	Environmental and sustainability impact of materials	0	0	6	12	7	0.73
	Healthy materials	0	0	8	11	6	0.76
Water	Water pollution	0	2	8	7	8	0.99

	Water resources	0	2	8	7	8	0.99
	Waste water treatment and disposal	0	2	6	9	8	0.95
	Water monitoring	0	3	9	10	3	0.87
	Water supply	0	3	9	6	7	1.03
	Construction	1	2	9	7	6	1.08
Energy	Energy supply	0	0	8	9	8	0.82
	Energy conservation and efficiency	0	1	6	8	10	0.91
	Energy monitoring	0	2	9	10	4	0.86
	daylighting	0	0	4	9	12	0.75
Climate change	Carbon management plan	0	0	7	12	6	0.73
	Social impact of climate change	1	2	10	8	4	1
	Physical impact of climate change	0	3	11	7	4	0.92
	Economics of climate change	1	2	12	6	4	1
Air quality	Ambient air quality	0	5	11	9	0	0.75
	Direct emissions	7	5	11	2	0	0.99
	Indirect emissions	9	7	7	2	0	1.0

With respect to the social pillar (SD =1.01) which has the highest SD among three pillars. The disagreement between sub-indicators within this pillar mainly goes back to the environmental activists who believed in higher importance of social pillar compared to others and specifically national policy makers and researchers, who scored this category as least important, which lead to the higher standard deviation in this category. Each with two and one respondents respectively.

Table 5.2: Questionnaire results of social pillar and associated Standard Deviation (SD)

Core indicator	Sub- indicator	Very poor	Poor	Moderate	Good	Very good	SD
Community facilities	Recreation	0	2	3	15	5	0.81
	Education	1	1	4	14	5	0.94
	Healthcare	2	3	7	10	3	1.11
	Retail	1	4	6	10	4	1.08
Culture	Cultural and religious facilities	2	1	6	13	3	1.04
	Use of environment	0	3	3	8	11	1.04
	Archaeology and local heritage	1	3	5	10	6	1.11
	Art	1	2	7	8	7	1.1
Form and space	Density, Depth, scale and massing	1	1	4	4	15	1.13
	Public, private and communal space	1	1	4	7	12	1.01
	Security	2	0	4	9	10	1.15
	Connectivity	0	1	2	13	9	0.76
Stakeholder engagement	Identification and analysis	1	1	5	12	6	0.99
	Engagement process and feedback	1	2	10	5	7	1.12
	Integrating stakeholders' comments	1	1	8	7	8	1.08
Health and wellbeing	Access to green space	0	2	6	4	13	1.05
	Community cohesion	0	0	9	9	7	0.81
	Institutions and social networks	2	9	14	0	0	0.65
	Indoor environment	0	1	5	13	6	0.79
	Social vibrancy	1	0	6	12	6	0.93
Transport	Public transport	2	1	8	4	10	1.27

	infrastructure						
	Pedestrian design and facilities	0	2	5	8	10	0.98
	Cycle design and facilities	1	2	7	10	5	1.04
	Waterways	2	2	9	6	6	1.19
	Freight traffic	3	8	8	5	1	1.06
	Private vehicle use	2	1	14	5	3	0.96
	Low emission vehicles	4	0	11	3	7	1.35
	Air travel	8	14	3	0	0	0.65

Some significant findings are as follows:

Indictors such as public transport infrastructure (SD = 1.27), low emission vehicles (SD =1.35), and waterways (SD = 1.19) have shown the highest disagreement, all located under 'transport'. Firstly, Table 5.2 reveals that for the 'public transport infrastructure' and 'waterways' sub-indicators, two respondents marked the indicators as 'very poor'. One of these was a national policy marker and researcher, and the other was a contractor. They considered all three indicators as having very poor impact on UUS. This opposed the other respondents, who considered these indicators as very important (for public transport infrastructure) or with moderate effect (waterways). On the other hand, 'low emission vehicles' were voted as very poor by 4 respondents, and within the whole table this category had the highest SD and, therefore, the most disagreement belongs to 'low emission vehicles'(SD = 1.35). It could be inferred that, as there are not many machines used in underground space, the respondents have given least importance to this category.

There are other indicators with high standard deviation such as 'healthcare' and 'archaeology and local heritages' both with (SD =1.11) or security (SD =1.15). Similarly, for the indicators ‘healthcare’ and ‘security’, two of respondents, of which one is a national policy maker and researcher and the other is from the contractor category, voted ‘very poor’, while for indicators ‘archaeology and local heritages’, one respondent voted very poor. However, other respondents agreed on good or very good impact of these indicators.

The economic pillar showed the lowest average standard deviation (SD = 0.89) compared to the other pillars, social and environmental, 1.01 and 0.95 respectively. This shows that respondents agreed on the impact of indicators on UUS to a similar extent. However, it can be seen that the national policy makers and researcher have given the most credit to this category, as opposed to the environmental activists, who showed the least interest in this pillar. The high interest of national policy makers and the researcher in this pillar, and generally the agreement between sub-indicator within this pillar, goes back to the high importance of economic considerations within construction activities. Meaning that environment, society and economic welfare are all limited to economic growth (Ekins, 1993). However, although the major conflict is between three respondents, nevertheless, due to the limited number of respondents, the impact is high.

Table 5.3 Questionnaire results of economic pillar and associated Standard Deviation (SD)

Core indicator	Sun-indicators	Very poor	Poor	Moderate	Good	Very good	SD
Facilities management	Usability	0	0	4	15	6	0.64
	Appropriate technologies	0	0	4	15	6	0.64
	Whole-life flexibility	0	2	4	11	8	0.91
	Operation and maintenance	0	1	5	10	9	0.86
Governance and reporting	Monitoring and evaluation	1	1	9	12	2	0.87
	Information disclosure and reporting	1	5	15	4	0	0.73
	Strategy	0	1	10	9	5	0.84

	Risk management	0	2	4	9	10	0.95
	Donations to voluntary and community organisations	11	9	5	0	0	0.78
Economic effect	Value for money	0	0	7	8	10	0.83
	Distortions to local economy	2	5	8	7	3	1.14
	Vitality and regeneration	0	1	5	11	8	0.84
	Carbon pricing	3	2	8	9	3	1.17
Employment and skills	Labour standards	0	3	9	8	5	0.96
	Training	0	5	8	5	7	1.12
	Access to finance	1	8	6	6	4	1.18
	Employment creation in construction	0	3	20	2	0	0.45
	Employment creation in operation	0	3	20	2	0	0.45
	Social mobility	2	3	10	7	3	1.09
Site selection	Site location	0	0	7	9	9	0.81
	Planning intent	0	3	17	5	0	0.57
	Diversity and mixed use	0	0	6	10	9	0.78
Procurement	Local sourcing	0	2	7	10	6	0.91
	Global sourcing	0	3	7	10	5	0.95
	Procurement strategy	0	4	8	6	7	1.08
Equality	Affordability	1	1	12	4	7	1.080
	Designing for equality	0	1	11	9	4	0.81
	Impacts and benefits	0	3	8	10	4	0.91
	lend tenure	1	4	9	7	4	1.1
	Displacement	3	2	11	6	3	1.14

Some disagreements on sub-indicates can be seen. There are six sub-indicators with very high SD, which have been listed below.

- Distortions to local economy (SD = 1.14); with respect to this sub-indicator 2 people have voted for 'very poor' impact on UUS. And another major group of respondents only considered this indicators with good impact however similar number of people also considered this sub-indicator with moderate impact. The variation between the numbers are the results of higher standard deviation.

- Carbon pricing (SD =1.17); similarly, for this indicator there is 3 respondents in very poor, and a large group of people with moderate and good impact.
- Displacement (SD = 1.14); again 3 respondents in very poor category and large number of people with moderate and good impact.

Experts who voted for very poor impact for these indicators were mainly the environmental activists and academics. This shows their lack of interest on the impact of projects on the local economy, as well as the carbon pricing. The low rank from academics can reflect the fact that economic and financial aspects are not, sometimes, considered in the research projects. However, their high importance is well identified by the respondents from the industrial groups.

Other three indicators belong to the employment and skills core indicator which shows high disagreement within this indicator:

- Training (SD =1.12)
- Access to finance (SD = 1.18)
- Social mobility (SD = 1.09)

As well as this, there are few other sub- indicators such as procurement strategy, affordability and land tenure with higher standard deviation compared to the rest of sub-indicators. However, participants had the most agreement within the sub-indicators of this pillar, as most of the standard deviations are low. In addition, the minor disagreement within this pillar comes mainly from national policy makers who have given the economic pillar very high score and have seen this element as the most important one, however this is in contrast with the rest of the participants. Hence, some disagreement and high standard deviation for some sub-indicators with this pillar can be seen.

Overall SD has been used as a way of representing the data and the results of the SD in the above tables indicated the agreement or disagreement between participants. The standard deviation presented in this section aimed to show the interest of groups of people in the three pillars of sustainability, and ultimately its sub-indicators. An underlying reason for the higher standard deviation in some indicators is the limited number of respondents.

The standard deviation demonstrated that national policy makers believed that the least important was the environmental pillar, while they have given a very high score to the economic pillar. The environmental activists, in contrast, believed the social and environmental pillar to be of higher importance, and the economic pillar to have low impact. This has led to the disagreement and, therefore, high standard deviation in some sub-indicators of economic pillar. Similarly with respect to the environmental pillar, national policy makers and researchers have given it as least important, in contrast with the other respondents, specifically academics and contractors.

Also, the environmental activists, construction material producers and manufacturers have all given higher importance to the social pillar compared to other respondents, specifically national policy makers and researchers which justifies higher standard deviation for some sub-indicators of this pillar.

However, this could be understood to go back to the limitation of the research, as there is only 1 national policy maker and researcher compared to 5 academics. There are other methods, such as Delphi, which includes inviting the respondents to a workshop after filling in the questionnaire to discuss the conflicts and disagreements (Thangaratinam and Redman, 2005). However, due to the time limitation of this research this was not possible.

The results presented in this research were obtained from a survey of the selected expert panels, and the fact that there was a limited number of respondents has to be considered, as it may have impacted upon the result. This section has shown the analysis results of the questionnaire responses, in which the calculated standard deviations present the distribution of the responses. The wide spread of some responses can be explained by the limited size of sample set and the limited number of respondents. Following up on the above tables, which have demonstrated the results of the questionnaire and the level of importance participants have given to each sub-indicator and the resultant standard deviation, the next section aims to demonstrate how the results from the questionnaire were used to attain a weighting for each sub-indicator.

5.4 Analysis of the Second Part of Questionnaire

As it has been explained preciously, there were eight main groups of respondents for the questionnaire. General analysis with respect to three pillars from the second part of the questionnaire are provided in this section.

- **Social**

The result of the questionnaire shows that the only one participant from client representative group has given high ranking to the sub-indicators of social pillar of questionnaire, meaning that most of the sub-indicators are given ‘neutral’, ‘good’ or ‘very good’. The results are similar for the two respondents from environmental activist. Out of the five respondents of the contractor group, three have also agreed on high importance of the most of the sub-indicators of this category. However, two respondents have given some indicators low ranking of 'very poor', such as 'cycle design and facilities', 'waterways' and 'freight traffic'. However, all five respondents of the contractor group agreed on poor performance of the sub-indicator 'air-travel'.

Similarly, among four respondents of the construction material producer and manufacturer group, three have given high ranking to most of the sub-indicators, except one respondent who has given sub-indicators, such as 'education' and 'cultural and religious facility' low ranking. And also most of the respondents of this group have given low ranking to the 'air travel' sub-indicator.

Within the four participating consultants, two of them agreed on the high importance of most of the sub-indicators of this pillar, and the other two have given low ranking to some of sub-indicators, such as' education' and 'healthcare', however, again they have all agreed on low importance of the 'air-travel' indicator.

Two respondents from the environmental activist group have both given high ranking to most of the sub-indicators, except one, who has given 'air quality' very low ranking. From the respondents of academic, local authority and policy makers, planners and national policy makers and researchers, all have agreed on more or less high importance of most of the sub-indicators, except that, again, they have all given the sub-indicator 'air travel' a very low indicator.

- **Environment**

The one respondent from the client representative group has given all sub-indicators of this pillar a high ranking. Out of five respondents of the contractor group, apart from one, all the other four have given all sub-indicators very high ranking. However, all five respondents have given the indicator 'air quality' very low ranking, specifically the sub-indicators 'direct emissions and 'indirect emissions'. Similarly, all four respondents of the construction material producer and manufacturer have ranked all sub-indicators high importance, except the sub-indicators of 'air quality'. From the consultant group, out of three respondents, two have given high importance to the sub-indicators. However, despite other groups considering air quality as not very important, all three respondents of this group have given the 'air quality' sub-indicator high ranking. Similarly, both respondents of the environmental activist group have also given high importance to these groups of indicators. Respondents from academics, as well as local authority, policy makers and planners, have provided high ranking to indicators of this pillar, again with the low ranking of 'air quality' sub-indicator from both of these groups. Last but not least, national policy makers and researchers have given 'air quality' high importance, in contrast to other groups, and similar to the consultant group.

- **Economic**

From the client representative group, there is a variety of ranking within this pillar, however the one respondent has given a very poor ranking to two sub-indicators of 'carbon pricing' and 'displacement'. From all five respondents within the contractor category, all have given high importance to most of the sub-indicators, except one respondent who has given some poor ranking to a few indicators, specifically 'carbon pricing', which has been ranked as very poor. Four participants within the consultant category have all given most of the indicators high ranking, except three respondents who have given 'donation to voluntary' a very low ranking. Similarly, from the environmental activist group, all indicators have been ranked high, except one respondent who has given 'donation to voluntary' very low ranking, and the other one has given low ranking to 'carbon pricing'. The pattern is similar for the other three groups of graduates, policy makers and local authority, as they have all given almost high ranking to all indicator, except the sub-indicator of 'donation to voluntary', and one respondent from government policy makers and researchers has given low ranking to the 'economic effect' indicator.

This section has given an insight into each group of respondent's opinions on sub-indicators. This has allowed the author to highlight which indicator has been given low rank, and should ultimately have a lower weighting in the calculation provided in the next section.

5.4.1 Detailed analysis

In order to analyse the results obtained from questionnaire and to calculate the weighting for indicators, a weighted average methodology was selected, similar to the one adopted by Gelman (2007). For each indicator, the weighted average has been calculated. Since the primary assumption was made on equality between three pillars of sustainability with respect to underground space, each pillar equals to 33.33%, all indicators have been calculated out of 33%. The final weighting for the indicators have been presented in Tables 5.5, 5.6 and 5.7.

Equation 5.1 is used to calculate the weighted average, developed from Arunagiri and Gnanavelbabu (2014) study. These weightings *(w)* determine the relative importance of each indicator on the average weighted value.

Equation 5.1

$$\overline{w} = \frac{\sum_{i=1}^{n} N_i \, s_i}{\sum_{i=1}^{n} N_i}$$

In which N is the number of responses (hits) and s is the score.

The use of Equation 5.1 for calculating weighted average is illustrated through an example in Table 5.4. For the indicator 'community facilities/ recreation' no one voted for very poor, 2 experts voted for poor, 3 for moderate, 15 good and 5 very good (as shown previously in Table 5.2). The weighted average for the indicators has been calculated as shown in Table 5.4, which is equal to 3.92 for this indicator. Ultimately, each calculated number has been recalculated out of 33 percent for the social pillar, which leads to a value of 1.283 for this indicator. In order to calculate the final weight for the core indicator, since the number of sub-indicators are different within each category, the average of the weights for the relevant sub-indicators has been considered.

Table 5.4: Weighted average methodology applied to 'community facilities/recreation'

Condition	Hits (N)	Score (s_i)	$N_i \times s_i$
Very Poor	0	1	0
Poor	2	2	4
Neutral	3	3	9
Good	15	4	60
Very good	5	5	25
$\sum_{i=1}^{5} N_i \, s_i$ = 0 + 4 + 9 + 60 + 25			98
$\sum_{i=1}^{5} N_i$ = 0 + 2 + 3 + 15 + 5			25
Weighted average ($\overline{w}$) = 98 / 25			3.92
Sum of Weighted average for the pillar (in this case Social)			101.84
Weighted average out of 33% = (3.92 / 101.84) x (33 / 100)			1.283

5.4.2.1 Environment

The final calculated weightings for the environmental pillar are presented in Table 5.5.

Table 5.5: Calculated weightings for environmental pillar

Core indicators (C)	Weighting (W)	Sub-indicators	Sub-weighting
(C_1) Soil and Land	***(W_1) [1.199]***	Contaminated land	W= 1.195
		Soil quality	W= 1.146
		Drainage systems	W = 1.255
(C_2) Biodiversity	***(W_2) [1.135]***	Protected species and habitats	W= 1.183
		Conserving and improving local biodiversity	W= 1.086
(C_3) Waste	***(W_3) [1.131]***	Construction waste management plan	W= 1.171
		Waste in operation	W= 1.134
		Hazardous / special waste	W= 1.074
		Designing out waste	W= 1.146
(C_4) Materials	***(W_4) [1.186]***	Materials efficiency in design	W= 1.243
		Use of recycled or reused materials	W= 1.098
		Environmental and sustainability impacts of materials	W= 1.219
		Healthy materials	W= 1.183
(C_5) Water	***(W_5) [1.126]***	Water pollution	W= 1.158
		Water resources	W= 1.158
		Wastewater treatment and disposal	W= 1.183
		Water monitoring	W = 1.062
		Water supply	W= 1.100
		Construction	W= 1.086
(C_6) Energy	***(W_6) [1.21]***	Energy supply	W= 1.207
		Energy conservation and efficiency	W= 1.231
		Energy monitoring	W= 1.098
		Daylighting	W= 1.303
(C_7) Climate Change	***(W_7) [1.08]***	Carbon management plan	W= 1.195
		Social impact of climate change	W= 1.050
		Physical impacts of climate change	W= 1.050
		Economics of climate change	W = 1.026
(C_8) Air quality	***(W_8) [0.76]***	Ambient air quality	W= 0.953
		Direct emissions	W= 0.700
		Indirect emissions	W = 0.628
Total		Total	33.33%

The highest weight belongs to the indicator ‘energy’ (W=1.21) followed by ‘soil and land’ (W=1.199), and the vote for least important goes to the ‘air quality’ (W=0.76) indicator. Energy is a global concern, especially when it comes to use of UUS. For example, Parker (2004) discusses the possibility of maintaining an underground facility and providing a pleasant environment with minimum energy usage or, alternatively, the use of energy extraction from underground.

Soil and land is an essential consideration for any UUS construction. The construction of underground works can result in ground movement around the excavation area. This ground movement can trigger incidents, such as collapses, subsidence and sinking, which can affect both the work under construction, as well as existing surrounding structures, especially if the construction is in developed urban areas (Gattinoni et al., 2014). Hence, in order to successfully plan construction of an underground facility, geotechnical information of the area is required such as soil properties, including contamination of soil (Simankina et al., 2016).

However, the lowest weighting within the whole table is for the core indicator of ‘air quality’ and, subsequently, its sub-indicators. All three-sub indictors within this category have a weighting of less than one, lower than the rest of tables. However, the air quality concerns have been highlighted in the literature by authors, such as instance Bong et al., (2013) or Demir (2015), who present some strategies for making improvements in air quality of underground facilities.

On the other hand, the result demonstrates that the highest weightings among the sub-indicators belong to the sub-indicator “daylighting”, which is a sensible result. Currently there is a concern regarding providing adequate daylight in underground spaces which refers to the high importance of this indicator (Carmody and Sterling, 1993; Goel et al., 2012). Underground space lacks access to natural daylight, therefore, in underground buildings, measures should be taken to ensure access to natural light in order to significantly alleviate many of the negative characteristics associated with sub-surface facilities (Bouchet and Fontoynont 1996; Hunt et al., 2016).

5.4.2.2 Social

Table 5.6 demonstrates the final calculated weightings for the social pillar in which 'form and space' indicator has the highest weighting (W= 1.355), followed by 'culture' (W= 1.23) and 'stakeholder engagement' indicator (W= 1.226). This is a sensible result evident from the literature, as form and space is an essential indicator, including concerns such as height, scale, connectivity and security of an underground project, which has been emphasised by Carmody and Sterling (1993). Also, the cultural aspect of UUS has been highlighted by authors such as Hunt et al., (2016) in that, for example Birmingham Library have been constructed using underground space. Stakeholder engagement is an important consideration for any construction activities (Manetti, 2011). However, within this category there are others that are deemed also to be important: the 'health and wellbeing' indicator has also been given a high weighting. It includes sub-indicators, such as 'access to green space' and having a desirable 'indoor environment', which has been indicated by CABE (2010) as an important consideration for UUS. The least weighting goes back to the 'transportation', (W=1.065). The low weighting of the transportation indicator goes back to the low weighting of its sub-indicators. There are two sub-indicators, 'freight traffic' and 'air travel', which are rated significantly lower than the other weightings in the whole table. This is an indication of the low importance of these two sub-indicators in the social pillars, with respect to UUS construction. This also reflects the current situation, in which underground is mainly used for public transportation, however, alternative means of transport, such as air travel, cannot be ignored.

Table 5.6: Calculated weightings for social pillar

Core indicators (C)	**Weighting (W)** ***[% Total]***	**Sub-indicators**	**Sub- weighting**
(C_9) Community Facilities	**(W_9)** ***[1.195]***	Recreation Education Healthcare Retail	W=1.283 W=1.257 W=1.100 W=1.139
(C_{10}) Culture	**(W_{10})** ***[1.23]***	Cultural and religious facilities Use of environment Archaeology and local heritage Art	W= 1.165 W= 1.335 W= 1.204 W= 1.217
(C_{11}) Form and Space	**(W_{11})** ***[1.355]***	Density, depth and scale and massing Public, private and communal space Security Connectivity	W= 1.388 W= 1.348 W= 1.309 W= 1.375
(C_{12}) Stakeholder Engagement	**(W_{12})** ***[1.226]***	Identification and analysis Engagement process and feedback Integrating stakeholders' comments	W= 1.257 W= 1.178 W= 1.244
(C_{13}) Health and Wellbeing	**(W_{13})** ***[1.202]***	Access to green space Community cohesion Institutions and social networks Indoor environment Social vibrancy	W= 1.348 W= 1.283 W= 0.812 W= 1.296 W= 1.270
(C_{14}) Transport	**(W_{14})** ***[1.065]***	Public transport infrastructure Pedestrian design and facilities Cycle design and facilities Waterways Freight traffic Private vehicle use Low emission vehicles Air travel	W= 1.231 W= 1.322 W= 1.191 W= 1.139 W= 0.890 W= 1.060 W= 1.100 W =0.589
Total		Total	33.33%

5.4.2.3 Economic

The weightings for economic pillar is presented in Table 5.7.

Table 5.7: Calculated weightings for economic pillar

Core indicator(C)	Weighting (W) *[% Total]*	Sub-indicators	Sub- weighting
(C_{15}) Facilities Management	**(W_{15})** ***[1.276]***	Usability	W=1.283
		Appropriate technologies	W= 1.282
		Whole-life flexibility	W =1.257
		Operation and maintenance	W =1.282
(C_{16}) Governance and Reporting	**(W_{16})** ***[1.003]***	Monitoring and evaluation	W=1.106
		Information disclosure	W=0.905
		Strategy	W= 1.169
		Risk management	W=1.282
		Donations to voluntary	W=0.553
(C_{17}) Economic Effects	**(W_{17})** ***[1.147]***	Value for money	W= 1.295
		Distortions to local economy	W= 0.993
		Vitality and regeneration	W= 1.270
		Carbon pricing	W = 1.031
(C_{18}) Employment and Skills	**(W_{18})** ***[1.02]***	Labour standards	W= 1.132
		Training	W= 1.119
		Access to finance	W= 0.993
		Employment creation in construction	W= 0.930
		Employment creation in operation	W= 0.930
		Social mobility	W= 1.018
(C_{19}) Site Selection	**(W_{19})** ***[1.182]***	Site location	W= 1.282
		Planning intent	W = 0.968
		Diversity / mixed use	W= 1.295
(C_{20}) Procurement	**(W_{20})** ***[1.165]***	Local sourcing	W= 1.194
		Global sourcing	W= 1.157
		Procurement strategy	W= 1.144
(C_{21}) Equality	**(W_{21})** ***[1.091]***	Affordability	W= 1.132
		Designing for equality	W= 1.144
		Impacts and benefits	W= 1.132
		Land tenure	W= 1.056
		Displacement	W= 0.993
Total		Total	33.33%

Results for the economic pillar (Table 5.7) indicate that the highest weighting belongs to the 'facilities management' (W=1.276) followed by the 'site selection' (W= 1.182) indicator, and the least weighting goes back to 'governance and reporting' (W=1.003). The high consideration given to the 'facilities management' indicator, which reveals the appropriateness of the facility for different users, as well as maintenance and flexibility of its lifecycle. For example, London Underground has an asset management strategy which highlights and covers the importance of these issues (Transport for London, 2013). As well as this, the importance of the choice of site location, with respect to UUS, has been emphasised in the literature, see for instance Vähäaho (2016) and Labbé (2016). Several studies specify the importance of site selection for a specific use of underground space, for example, Xue (2015) reports that site selection is the first stage in underground water-sealed petroleum storage construction. The 'governance and monitoring' indicator has the least weighting, mainly because of the low weighting of the sub-indicators 'information disclosure' and 'donations to voluntary'. Although the core indicators weighting is still not very low, this indicates the higher importance of aspects of, for example, risk and evaluation, rather than donations to organisations.

Within this pillar, among sub-indicators a range of different weightings from low 'employment creation in construction and operation' (W = 0.93) to high 'diversity and mixed use' (W = 1.295) can be observed.

The top sub-indicator within the economic pillar is 'value for money' (under 'economic effect') and 'diversity and mixed use' (under 'site selection') both equal to W=1.295. With respect to value for money, UUS construction costs more than above ground, however maintenance would be cheaper and it lasts longer, as discussed by Parker (2004). Therefore, it is crucial to find out whether the project is feasible. The relatively increased weighting given to 'diversity and mixed use', highlights the fact that UUS construction offers a variety of opportunities and facilities that are considered more desirable.

Having used questionnaires and calculating the weighting from the obtained results, in the next section another method is used by the author to verify the calculated weightings.

5.5 Weighting Validation: Alternative Method of AHP

In order to verify the weightings that have been received from the questionnaires and experts, Analytic Hierarchy Process (AHP) method was applied in this research. AHP is a popular technique for obtaining the weighting within a decision-making tool. For example, similar methodology has been undertaken by Namini et al., (2013), which has developed a managerial sustainability assessment tool for buildings in Iran, and used AHP to develop weighting for the selected criteria.

AHP was first developed by Saaty (1980), and aims to solve decision-based problems, based on the deterministic expression of preference when multiple alternatives exist. In this method priority value of each alternative is given using relative comparison from multiple combinations of criteria and alternatives (Koo et al., 2009).

Derived from AHP, the relative importance of each criterion in comparison with each other is determined based on a review of previous research and experience gained from similar projects. In this research, the quantified values were based on the author's and Mr

Braithwaites' engineering judgment and experience (explained in Chapter 3, Section 3.2.2.4). The steps of AHP development are as follows.

Step 1- Structuring the hierarchy: The first steps is establishing the problem in the form of a hierarchical model. For this study, a three-level AHP model was developed in which the highest level represents the 'goal' (i.e. sustainable development of UUS), intermediary level represents the 'overarching criteria', in this study are the main pillars of sustainability (i.e. environment, social, economic), the importance of which for UUS has been assumed equal. Lowest level represents the 'subsidiary criteria', which in this study are 'core indicators' in each pillars of sustainability (Figure 5.3). The 'n' subsidiary criteria, which are in the same level, are compared using Saaty's scale (explained in Step 2).

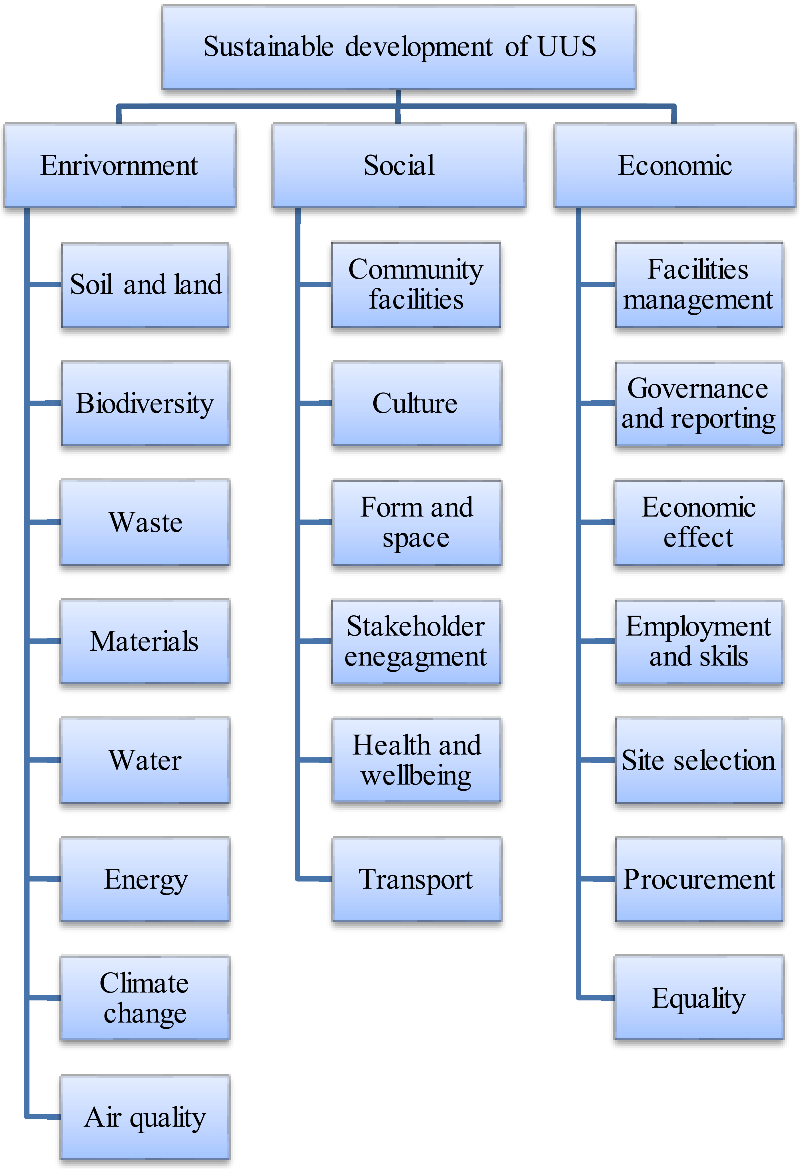


Figure 5.3: Structure of the utilised three-level AHP model

Step 2- Obtaining the criteria' weighting: The second step involves making a comparison matrix to determine the relative importance of each alternative in the same level. These qualitative pairwise comparisons are assigned values according to the scale (9, 8, 7, 6, 5, 4, 3, 2, 1, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9) introduced by Saaty (1980). To find the weighting for 'n' criteria, the following equation (Equation 5.2), developed by Aragonés-Beltrán et al.,

(2014) is used to find the number of required comparisons.

<u>*Equation 5.2*</u>

$$N = \frac{(n^2 - n)}{2}$$

In which N is the number of required comparisons and n is the number of criteria.

Step 2.1- Making comparison matrix: Within the environment, social and economic pillars there are eight, six and seven core indicators respectively. Using Equation six, the number of comparisons in each pillar is equal to 28, 15 and 21 for environment, social and economic pillars respectively. The calculations for the environmental pillar are demonstrated in this section (the calculations for social and economic pillar are presented in Appendix C). A matrix evaluating results of the 'subsidiary criteria', with respect to the overall 'goal' is obtained, following instructions used by Triantaphyllou and Mann (1995) and Curiel- Esparza and Canto-Perello (2013). The diagonal elements of the matrix are always one and it is only necessary to fill up the upper triangular matrix. The following rules has to be followed to fill the upper triangular matrix:

1. *If the judgment value is on the **left** side of 1, we put the **actual judgment** value.*
2. *If the judgment value is on the **right** side of 1, we put the **reciprocal** value.*

In short, to fill the lower triangular matrix, the reciprocal values of the upper diagonal is used. If α_{ij} is the element of row i column j of the matrix, then the lower diagonal is filled using the following formula.

Equation 5.3

$$\alpha_{ji} = \frac{1}{\alpha_{ij}}$$

Then Equation 5.4 is used to compare N elements (i.e. number of criteria, for example C_1 to C_n, and specify the relative weighting (priority or significance) of C_i with respect to C_j) by αij and form a square matrix A= (αij) of order n with the constraints that αij = 1/αji, for i ≠ j, and αii = 1. Such a matrix is called a reciprocal matrix.

Equation 5.4

$$A n \times n = (aij)\ n \times n = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} & 1 & \dots & a_{2n} \\ \vdots & \vdots & 1 & \vdots \\ a_{n1} & a_{n2} & \dots & 1 \end{bmatrix} \text{ where } a_{ji} = \frac{1}{a_{ij}} \qquad i, j = 1,2,\dots,n$$

Pairwise comparisons are done within the three pillars' core indicators. For example, for the environmental pillar, 'energy' indicator has been considered more important than all other indicators, except 'climate change', which is given the same importance. This reflects the associated emphasis in the literature on the high importance of energy issues and the fact that energy assessment, due to the high consumption of energy, urbanisation and growth of population, has to be considered more carefully (Tian et al., 2016). Similarly, 'water' indicator has been considered to have a higher importance, compared to all other indicators except 'climate change' and 'energy demand', which are of equal importance. The reason for this is that an appropriate source of potable water is a necessity for health and wellbeing of humans and ecosystem, as well as for social and economic development. However, nowadays potable water sources have become a serious threat (UN-Water, 2014). Similarly, 'climate change' has been considered to have the same importance with all remaining indicators, except 'air quality' and 'biodiversity', and this goes back to the fact that climate change has been a concern in the past few decades and has pressurised both society and environment. The resultant degradation is translated into the form of changing weather patterns that threaten food production or influence sea level, which increase the risk of flooding (United Nations, 2017). According to Bobylev (2016), UUS has the potential to mitigate climate change in ways such as lowering energy consumption by a significant amount, or providing alternative locations for facilities at risk from climate change effects (Bobylev, 2016).

With respect to the 'materials' indicator, it has only been considered more important than 'air quality' and 'biodiversity'. It stems from the high importance of materials selections for construction projects, for example Jahan et al., (2016) highlights the high importance of the selection of appropriate materials, and the fact that it impacts different aspects of a project, including usability, customer, operating environment and costs. However, although material is an important consideration, especially compared to air quality and biodiversity, other indicators such as water and energy are identified as more essential.

The only indicator that has been considered less important compared to others is 'air quality'. It should be noted that although UUS can impact air quality in our environment, however, when compared to other indicators, it is less important. Hence, the reciprocal matrix for environmental pillar, according to the above judgement, is given in Table 5.8.

Table 5.8: Environmental pillars' AHP matrix

	Soil and land	Biodiversity	Waste	Materials	Water	Energy	Climate change	Air quality
Soil and land	1	2	0.1429	1	0.3333	0.1429	1	2
Biodiversity	0.5	1	0.3333	0.3333	0.3333	0.3333	0.3333	1
Waste	7	3	1	1	0.3333	0.3333	1	3
Materials	1	3	1	1	0.3333	0.3333	1	2
Water	3	3	3	3	1	1	1	3
Energy demand	7	3	3	3	1	1	1	3
Climate change	1	3	1	1	1	1	1	3
Air quality	0.5	1	0.3333	0.5	0.3333	0.3333	0.3333	1

Step 2.2- Priority Vectors: Having a comparison matrix (Table 5.8), it is now required to compute priority vector, also called normalised principal Eigen vector, which is the normalized Eigen vector of the matrix. Firstly, the total sum of each column of the reciprocal matrix has to be calculated (Table 5.9), thereafter, each element of the matrix is divided by the sum of its column, the result is normalized relative weight (Table 5.10) where the sum of each column is one.

The normalised principal Eigen vector, which is in fact the weightings of the elements, is then obtained by averaging across the rows (Table 5.11).

Table 5.9: Environmental pillars' AHP calculations

	Soil and land	Biodiversity	Waste	Materials	Water	Energy	Climate change	Air quality
Soil and land	1	2	0.1429	1	0.3333	0.1429	1	2
Biodiversity	0.5	1	0.3333	0.3333	0.3333	0.3333	0.3333	1
Waste	7	3	1	1	0.3333	0.3333	1	3
Materials	1	3	1	1	0.3333	0.3333	1	2
Water	3	3	3	3	1	1	1	3
Energy demand	7	3	3	3	1	1	1	3
Climate change	1	3	1	1	1	1	1	3
Air quality	0.5	1	0.3333	0.5	0.3333	0.3333	0.3333	1
Sum	21	19	9.80952	10.83333	4.66667	4.47619	6.66667	18

Table 5.10: Normalized relative weight for environmental pillar

	Soil and land	Biodiversity	Waste	Materials	Water	Energy	Climate change	Air quality
Soil and land	0.04762	0.105263	0.0145631	0.0923077	0.071429	0.031915	0.150000	0.111111
Biodiversity	0.02381	0.052632	0.0339806	0.0307692	0.071429	0.074468	0.050000	0.055556
Waste	0.33333	0.157895	0.1019417	0.0923077	0.071429	0.074468	0.150000	0.166667
Materials	0.04762	0.157895	0.1019417	0.0923077	0.071429	0.074468	0.150000	0.111111
Water	0.14286	0.157895	0.3058252	0.2769231	0.214286	0.223404	0.150000	0.166667
Energy demand	0.33333	0.157895	0.3058252	0.2769231	0.214286	0.223404	0.150000	0.166667
Climate change	0.04762	0.157895	0.1019417	0.0923077	0.214286	0.223404	0.150000	0.166667
Air quality	0.02381	0.052632	0.0339806	0.0461538	0.071429	0.074468	0.050000	0.055556
Sum	1	1	1	1	1	1	1	1

Table 5.11:Eigen value calculations for environmental pillar

	Soil and land	**Biodiversity**	**Waste**	**Materials**	**Water**	**Energy**	**Climate change**	**Air quality**	**Eigen vector**
Soil and land	0.04762	0.105263	0.0145631	0.0923077	0.071429	0.031915	0.150000	0.111111	0.07803
Biodiversity	0.02381	0.052632	0.0339806	0.0307692	0.071429	0.074468	0.050000	0.055556	0.04908
Waste	0.33333	0.157895	0.1019417	0.0923077	0.071429	0.074468	0.150000	0.166667	0.14351
Materials	0.04762	0.157895	0.1019417	0.0923077	0.071429	0.074468	0.150000	0.111111	0.10085
Water	0.14286	0.157895	0.3058252	0.2769231	0.214286	0.223404	0.150000	0.166667	0.20473
Energy demand	0.33333	0.157895	0.3058252	0.2769231	0.214286	0.223404	0.150000	0.166667	0.22854
Climate change	0.04762	0.157895	0.1019417	0.0923077	0.214286	0.223404	0.150000	0.166667	0.14426
Air quality	0.02381	0.052632	0.0339806	0.0461538	0.071429	0.074468	0.050000	0.055556	0.05100
Sum	1	1	1	1	1	1	1	1	

Step 3 – The third step involves determining the consistency ratio. Consistency ratio (CR) is used to assess ranking consistency and is calculated by dividing the consistency index by the random consistency index, as described by Saaty (1980). Generally, a consistency ratio of 0.10 or less is advised (Saaty, 1980). If CR is less than a threshold value then the matrix can be considered as having an acceptable consistency, and the derived priorities from the comparison matrix are meaningful.

Consistency ratio is calculated as follows:

<u>*Equation 5.5*</u>

$$CR = \frac{CI}{RI}$$

Where RI is Random Index (described below),

<u>*Equation 5.6*</u>

$$\boldsymbol{CI = \frac{(\lambda_{max} - n)}{(n-1)}}$$

λ_{max} is the maximum eigenvalue of the matrix.

The RI, in Equation 5.5, is an experimental value which depends on n value. Table 5.12 shows the RI values suggested by Saaty (1994).

Table 5.12: RI values (Saaty, 1994)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Step 3.1- In order to check the consistency ration, λ_{max} should be calculated. Principal Eigen value is obtained from the summation of products between each element of Eigen vector and the sum of columns of the reciprocal matrix. Hence the λ_{max} is calculated as following:

λ_{max}= (21 × 0.07803) + (19 × 0.04908) + (9.80952 × 0.14351) + (10.83333 × 0.10085) + (4.66667 × 0.20473) + (4.47619 × 0.22854) + (6.66667 × 0.14426) + (18 × 0.05100) = 8.929533

Hence $CI = \frac{(8.929533-8)}{(8-1)} = 0.13279$ (Using equation 5.6)

And subsequently

$CR = \frac{CI}{RI} = \frac{0.13279}{1.41} = 0.09$ (Using equation 5.6)

The results from AHP, with respect to three pillars of environment, society and economy, have been given in Table 5.13. The table demonstrates the weightings for each core indicator.

Environmental pillar results from the questionnaire demonstrate that the top priority indicator is 'energy', followed by 'soil and land'. This is followed by 'materials' and 'biodiversity' and 'waste', of equal importance, followed by 'water'. The lowest two weightings belong to 'climate change' and 'air quality' accordingly.

However, according to AHP results, 'energy' is the top indicator with the highest weighting, which confirms the findings of the questionnaire. This is followed by 'water' and 'climate change', which differs from the findings of the questionnaire, as those two are emphasised in the literature as the main challenges. It appears that respondents of the questionnaire believe that, in reality, for an UUS project, 'air quality' is the least important indicator, in contrast, AHP results show that 'biodiversity' is the least important indicator, and this is followed by 'air quality'.

As for the social pillar, the highest weightings belong to 'form and space', 'culture' and 'stakeholder', and the lowest weighting to 'transport'. In contrast, AHP results indicate that 'transport' has the highest weighting, and this is followed by 'health and wellbeing' and 'form and space', and the lowest weighting belongs to 'culture'. The high weighting of 'transport' from AHP is the lowest weighting from the questionnaire, which demonstrates that, although underground transportation is an important aspect within UUS construction, as discussed in literature review, respondents only voted for public transportation consideration and have given very low credit to other aspects of UUS transportation form, hence, lower weighting from the questionnaire. AHP results within this pillar show the disagreement between findings from the literature and the respondents' views.

The results of questionnaire for the economic pillar show that 'facilities management', 'site selection', 'procurement' and 'economic effect' are the top weighted indicators, and the least weighting goes back to 'governance and reporting'. Compared to AHP results, it shows that 'employment and skills', 'equality' and 'facilities and management', and 'governance and reporting' are top four indicators, with the highest weightings accordingly. Except the 'facilities management', which was also confirmed by the questionnaire results, the high importance of the other three indicators in AHP is because they have been highlighted in literature. For example, the contribution of UUS projects, in terms of employment, or how poor governance can cause delay to projects (Gorshkov and Epifanov, 2016; Bobylev, 2016). However, respondents considered other indicators, such as ‘facility management’ and ‘site selection’ more important, site selection and the planning for long-term use of site is an essential step. The lowest weighting within AHP belongs to ‘procurement’, which differs from the questionnaire results. Although there has been more emphasis on other indicators within literature, procurement, with respect to UUS, plays a major role, one of which is the issue of ownership of UUS, which needs to be resolved (Vähäaho, 2014).

Table 5.13: AHP results

Environment pillar		**Social pillar**		**Economic pillar**	
Core indicators	**Weighting (w)**	Core indicators	**Weighting (w)**	**Core indicators**	**Weighting (w)**
Soil and Land	0.07803	Community Facilities	0.0670	Facilities Management	0.1191
Biodiversity	0.04908	Culture	0.0486	Governance and Reporting	0.1110
Waste	0.14351	Form and Space	0.0814	Economics effect	0.0923
Materials	0.10085	Stakeholder Engagement	0.0676	Employment and skills	0.2684
Water	0.20473	Health and Wellbeing	0.1922	Site selection	0.0962
Energy	0.22854	Transport	0.5432	Procurement	0.0666
Climate Change	0.14426			Equality	0.2465
Air quality	0.05100				
Consistency ratio	**0.09**	**Consistency ratio**	**0.09**	**Consistency ratio**	**0.10**

5.6 Summary

A questionnaire has been developed in order to obtain weightings for the identified indicators. This chapter has described findings from the questionnaire, which was filled in by experts in the UUS field. A weighted average methodology has been applied and each pillars of sustainability have been considered equally therefore the final numbers have been calculated as 33.33 percent of the total for each indicator. The final weighting for the indicators obtained from the expert panel, presented in Tables 5.5, 5.6 and 5.7. Additionally, an alternative approach of AHP has been utilised to verify the developed weightings. AHP has been undertaken using the author's and Mr Peter Braithwaites' knowledge and experience within this field. The results of AHP differ from the questionnaire to some degree, but this is mostly a reflection of the literature, however, the questionnaire is the response of the experts. Hence, the results of questionnaire have been used for this research. The resulting USPeAR, constitutes a robust decision-making tool with an appropriate weighted indicator system. The application of this tool is demonstrated in the following chapter through the use of two case studies.

CHAPTER 6: TWO CASE STUDIES

The aim of this research was to produce a tool capable of evaluating the contribution of UUS towards sustainability of our environment, or alternatively determining the sustainability performance of a facility, which is planned to go underground. For so doing, a tool, named USPeAR, has been developed, which comprises a series of indicators with associated weightings to be used for evaluating UUS. To this end, this chapter details on how to use the tool by demonstrating its application through two case studies, both of which are stations:

- Case Study 1: *Farringdon Station, London, UK* - awarded CEEQUAL excellent. Therefore, the aim of using USPeAR here is to verify the results with CEEQUAL results, and to present the station as the best case (ideal performance) of a UUS project, ultimately being able to use the project as a benchmark for Aghdasiyeh Station (Section 6.2),
- Case Study 2: *Metro Line 3, Aghdasiyeh Station, Tehran, Iran* – an under-performing case study in terms of sustainability. The point of using USPeAR in this case is to highlight its benefits when applied under completely different context and conditions to Case Study 1. In other words, to show how the tool can be used to evaluate the performance of a station project with low sustainability credentials and highlight ways to improve it, drawing from the exemplar Crossrail project (Section 6.3).

6.1 Implementing the Tool

To demonstrate the application of the developed tool, the following methodology was used to assess case studies with respect to UUS use:

1) For each case study, two sustainability professionals within the projects attended a series of meetings with the author in order to undertake the USPeAR assessment (details previously described in Chapter 3), during which the goals and scope of the projects were discussed with the team. These two steps are shown in the first sheet of the USPeAR tool (Figure 6.1).

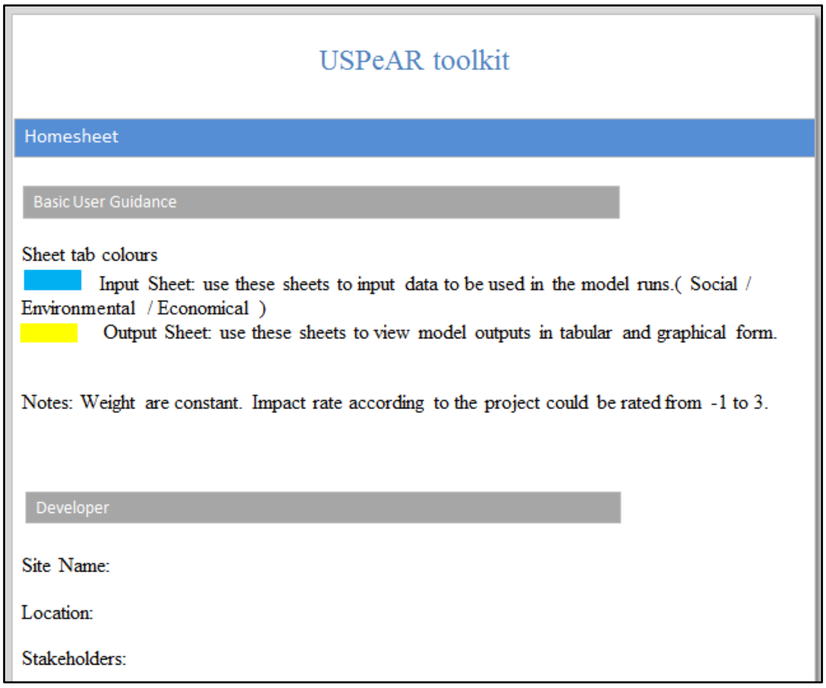


Figure 6.1: Snapshot of steps 1 and 2 of the tool

2) The guided questions (Appendix D) for each indicator within the developed tool were discussed during separate meetings held with the project staff. During these meetings project performance was considered against each of the guided questions which

were discussed and the results deliberated upon. Each indicator was specifically assessed and performance duly determined. The indicators were scored from values of, or sub-standard (-1) to exemplary (3) and these values were placed into the tool. A snapshot of economic pillar has been given in Figure 6.2.

3) A graphical representation of each case study's performance was given to aid analysis and reflect upon the results found. The chart shows not only the value assigned (-1 to +3) but also the weightings – The higher the weighting is applicable the indicator segment will take up a bigger % of the pie (Figure 6.3 and 6.4).

4) Lastly the USPeAR output was compared with that of SPeAR® and observations were made and commented upon.

The following section presents the case studies assessment and the results.

Inputsheet: Economic

Indicator / *Sub-indicator*	Weight	Scoring	Narrativves
Facilities management (1.276)			
Usability	1.283	3	
Appropriate technologies	1.282	3	
Whole-life flexibility	1.257	3	
Operation and maintenance	1.282	3	
Governance and reporting (1.003)			
Monitoring and evaluation	1.106	3	
Informatiom disclosure and reporting	0.905	3	
Strategy	1.169	3	
Risk management	1.282	3	
Donations to voluntary and community organisations	0.553	3	
Economic effect (1.147)			
Value for money	1.295	3	
Distortions to local economy	0.993	3	
Vitality and regeneration	1.27	3	
Carbon pricing	1.031	3	
Employment and skills (1.02)			
Labour standards	1.132	3	
Training	1.119	3	
Access to finance	0.993	3	
Employment creation in comstruction	0.93	3	
Employment creation in operation	0.93	3	
Social mobility	1.018		

Indicator / *Sub-indicator*	Weight	Scoring	Narratives
Site selection (1.182)			
Site location	1.282	3	
Planning intent	0.968	3	
Diversity and mixed use	1.295	3	
Procurement (1.165)			
Local sourcing	1.194	3	
Global sourcing	1.157	3	
Procurement strategy	1.144	3	
Equality (1.091)			
Affordability	1.132	3	
Designing for equality	1.144	3	
Impacts and benefits	1.132	3	
Land tenure	1.056	3	
Displacement	0.993	3	

Figure 6.2: Snapshot of Stage 2; scoring for economic pillar

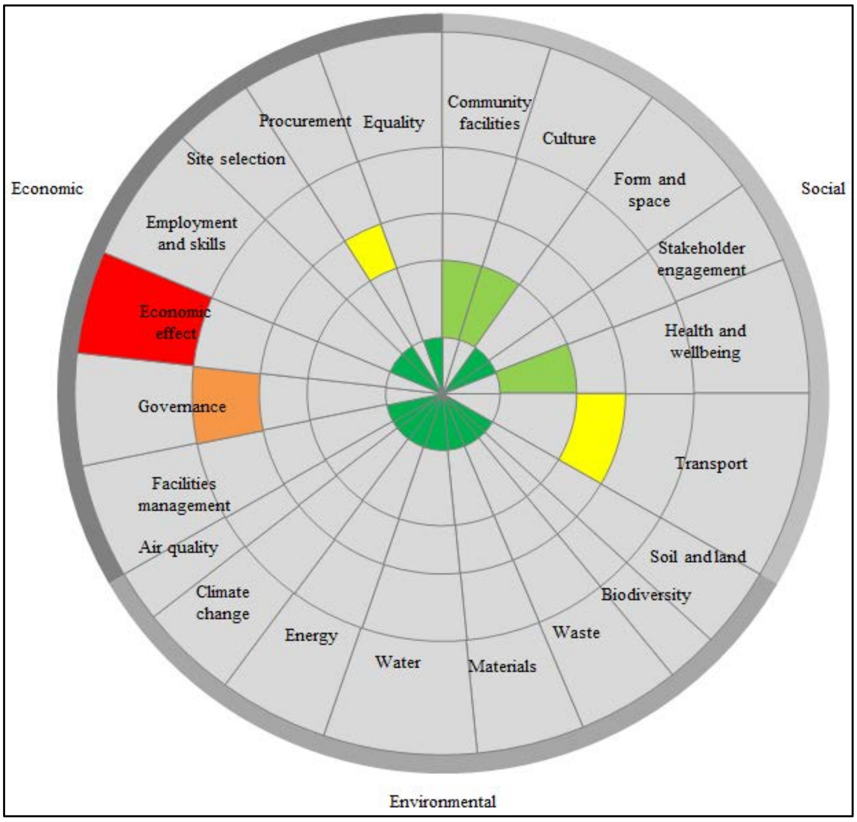


Figure 6.3: Snapshot of the output diagram

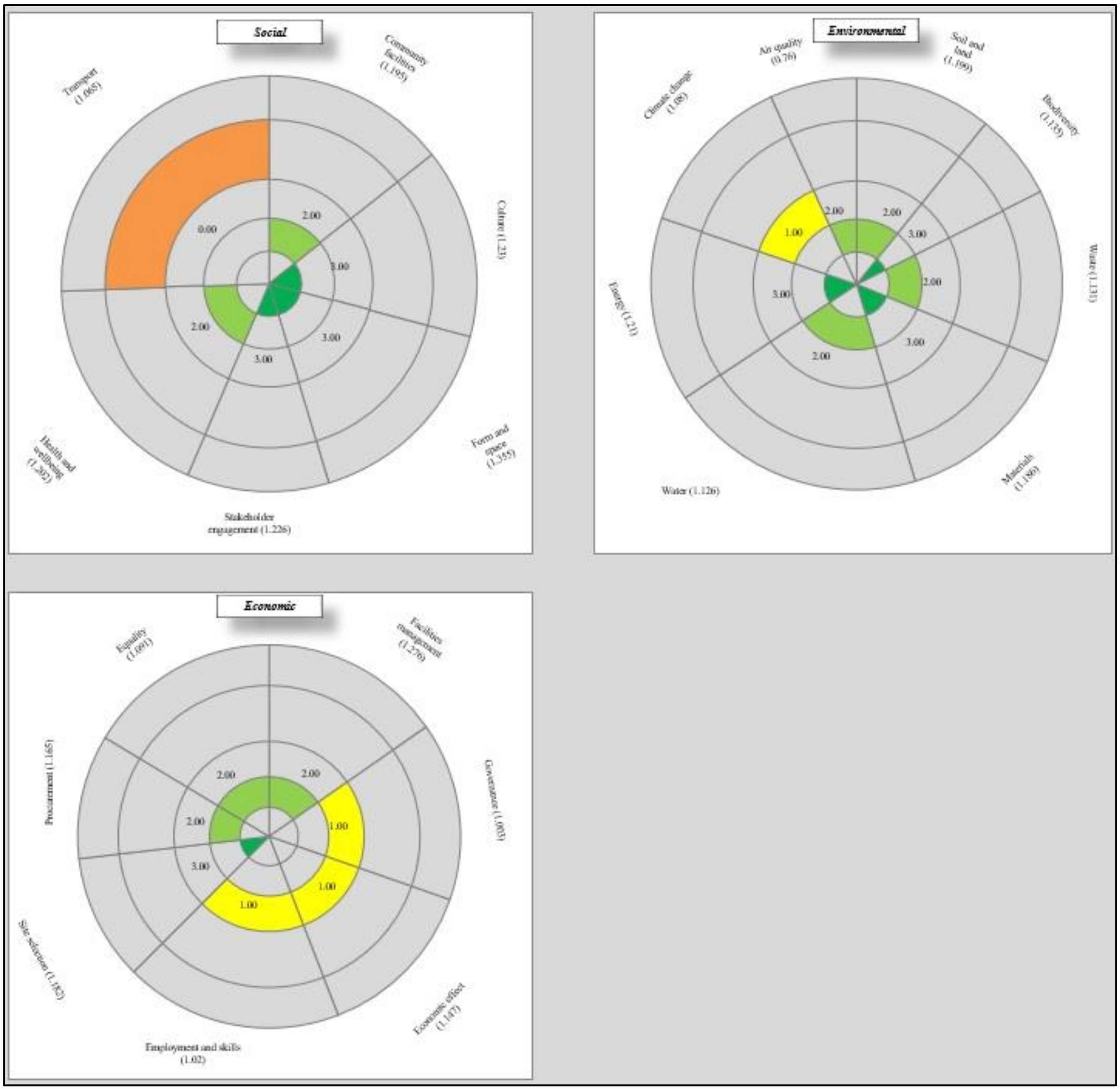


Figure 6.4: Snapshot of the outputs for three pillars of sustainability

It should be noted that the assessment must be a continuous process, with a view to conducting a number of assessments at different stages of the project cycle. Furthermore, feedback obtained from stakeholders needs to be progressively incorporated in each subsequent assessment. Any changes made to the project based on the assessment result should be updated to the USPeAR to ensure the relevance of the analysis to the next stage of the project. SPeAR® recommends that the tool can be used throughout a project where sustainability appraisal is required, from initial design through to operation. It is important to note that Arup (2016) states that SPeAR® is not just a series of independent indicators, but a range of virtuous cycles that can be created. As defined by Arup (2015a) virtuous cycles can be made for example, if a site provides an opportunity for easier access to public transport and is in close proximity to make cycling and walking more attractive, this will have impact on air quality. This rule applies to USPeAR as well.

6.2 Case study 1: Farringdon Station

Farringdon Station, once completed will be "the heart of the heart" of Crossrail. It will be the only station in London with interchanges between Crossrail, London Underground services and the Thameslink network (Figure 6.5) (Crossrail, 2016).

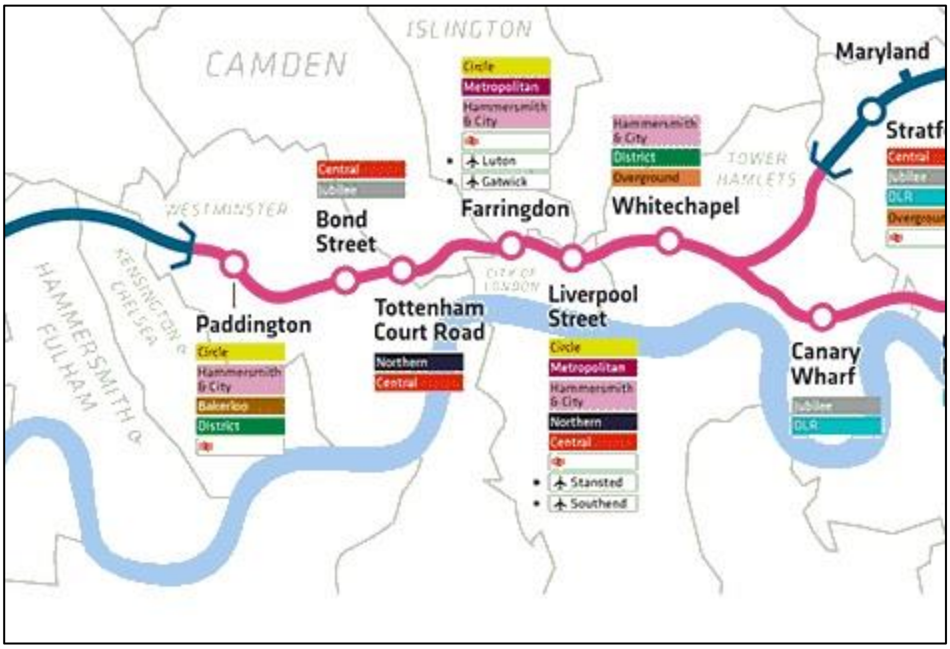


Figure 6.5: Orientation location plan (Crossrail, 2016)

According to CEEQUAL (2016), as part of the £6 billion Network Rail Thameslink Programme (TLP), Farringdon Station is one of the three central London stations that are being redeveloped to improve connections for trains and, accordingly, passengers. It has been estimated that there would be 102,000 passengers per day using this station by 2026 (City of London Corporation, 2015).

The station is owned and operated by London Underground and its location is within a very dense area, built-up with a range of commercial, residential and conservation areas. There would be two new ticket halls: a western facility at Farringdon Road and an eastern equivalent at Lindsey Street (Barbican) (Figure 6.6). This significant transport exchange site has needed to be built within a complex infrastructure network up to 25 metres below ground (Crossrail, 2017).

Farringdon Station is well-known to those who reside within the area as one of the major redevelopments in London’s transport investment. As such, the station can be considered as one of the biggest projects, and one of the most challenging of its kind in London, if not Europe. Excavating 42km of tunnels through London’s complex and crowded subterranean world, requires the construction of brand new stations and infrastructures within the most densely occupied area within the city of London. Therefore, it is a highly ambitious project that will becomes one of the busiest transport centres in London when the network opens in 2018 (Rail Engineer, 2014; Network Rail, 2016).

The opportunity Farringdon Station exploits is that it is known to be the only station in London to provide direct access to three of the city’s five airports: Heathrow, Gatwick and Luton. There would be 140 trains per hour and transportation of up to 150,000 passengers per day through the station is planned for the time the Crossrail services are in full operation (Rail engineer, 2014; Network Rail, 2016).

Figure 6.6: A snapshot of eastern ticket hall of the Farringdon Station

6.2.2 Sustainable UUS use within Farringdon Station

Sustainability has been the central embodiment of the Thames Link Programme by conveying 20 manageability goals through design and construction (Network Rail, 2014). The main key driver was to gain best performance in sustainable design and construction.

The project team's aim was to accomplish a standard higher than 'basic', and by the time the Farringdon Station redevelopment project was registered under CEEQUAL, a target had been set to achieve a rating of 'excellent'. Finally, in 2012, Farringdon Station was awarded one of Thameslink's highest CEEQUAL Whole Project Award scores of 90.3% (CEEQUAL, 2016). The assessment is based on the following criteria (CEEQUAL, 2016):

- heritage and town planning requirements;
- noise and nuisance;
- piling into the aquifer;
- designing out waste;
- community relations and engagement;
- energy and carbon;
- material use and sustainable procurement; and
- ecological habitat creation.

In this research, knowing the excellent performance of the Farringdon Station, it was selected for the assessment to form the 'benchmark' for the second case study and against which to be compared. This benchmark can also be utilised for assessing any other USS project, as an evidence and example on how sustainable measures could/should be taken in a project.

6.2.3 Scoring of indicators for Farringdon Station

To assess the performance of the station, indicators were evaluated and discussed during meetings held with Farringdon Station team, the Head of Sustainability of Crossrail and Site Manager of Farringdon Station (meeting details are presented in Chapter 3). Indicators' performance has been reviewed and evidence provided. Details of the indicator analysis are provided in Tables 6.1 (a, b, c). Justifications were piloted on the indicators based on the team opinion and evidence (where available) provided. The data collected has been rated from -1 to 3, or worst case to best case. The justifications given in the tables contain information collected during these meetings, and also from documents concerning Farringdon Station, such as the Environment Management Plan, Farringdon main station - CRL Document Number: C435-BFK-T1-GPD~M123-50002, to which access permission was granted.

Table 6.1a: Environmental pillar assessment and scoring for Farringdon Station

Core indicator	Sub- indicator	Score	Justification
(C_1) Soil and land	Contaminated land	3	Farringdon site has been assessed by Crossrail as potentially contaminated. Based on the review of the site information there is a slight chance of contamination on the site, however this will be thoroughly checked. A land contamination management plan will be developed including measures and mitigations for the potential contamination. There is also a risk of water contamination, for which there is a remedy planned if needed.
	Soil quality	3	Soil assessment has been undertaken prior to the project and it has been completely removed.
	Drainage systems	3	Sustainable drainage systems have been used and the risk of site run off has been managed. There was a large site for which Grey water has been used during construction. The Water Management Plan consists of a site drainage plan to identify drains and surface water flows, and detail collection and any necessary treatment of surface runoff. The plan will be kept onsite and briefed to all personnel during the site-specific induction.
(C_2) Biodiversity	Protected species and habitats	3	Crossrail works at Farringdon are around a highly built-up urban area with open space surrounded by small parks which means the surrounding areas are in a conservation area with several trees having tree preservation orders (TPOs). Not many animal species or communities have been noted; however, ecological management will be continually monitored.
	Conserving and improving local biodiversity	3	The adopted Environment Policy provides targets to achieve environmental and social development with a view to continuously improve the service. Also, fundamental to this project, particularly in this initial phase, is the principle of sustainability, which includes biodiversity.
(C_3) Waste	Construction waste management plan	3	There was a strategy in place for the waste management. For example, the target was to recycle 95% of the excavated materials together with other example plans such as vehicles carrying waste being monitored. There has been commitment to the BREEAM and CEEQUAL programmes through utilised waste minimisation methods, and any unavoidable waste materials generated will be reused or recycled where possible. Reuse will occur within the project, but beneficial reuse of materials on other projects will also be considered in line with best practice.
	Waste in operation	3	Each station has been provided with bin storage and there is a collection plan in place through traditional methods.

	Hazardous/special waste	3	During the construction of Farringdon Station, hazardous waste was found through a demolition questionnaire and this required a waste strategy to be put in place. In addition, contaminated ground was found and accordingly there was a plan put in place for this also.
	Designing out waste	3	There is a plan for waste management which will be produced and updated by the environmental manager within a minimum time scale of every 6 months. The plan was produced in accordance with the site management plans regulations (2008) prepared by DEFRA. There is a plan for potential waste arising and the design process considered designing for reuse and recovery and off site construction. For example, steel has been reused from another site, and returned back to the supplier to be melted back and reused. A waste management plan was produced in the design phase of the project and waste collection areas been designed according to standards.
(C_4) Materials	**Materials efficiency in design**	3	As part of the project there are targets to integrate number of sustainability criteria for example using low volatile organic compound (VOC) or no VOC products (carbon-based substances that easily evaporates or "off-gases" at room temperature), such as high efficiency LED lighting as well as, ensuring ethical supply of materials through regulations, and A or A+ rated insulation materials.
	Use of recycled or reused materials	3	Recycled content within materials and construction components have been calculated using environmental data reporting tool. As identified within the project's objectives, this will target 15% of the total material value to be derived from reused and recycled content in new construction and aim to exceed 20%. A final report detailing the percentage achieved will be submitted to the project manager upon completion of the project.
	Environmental and sustainability impacts of materials	3	A procurement plan has been developed for procuring both the services of sub-contractors and materials, which integrate key environment and sustainability aspects required to comply with the Works Information and requirements as a minimum. As part of this process subcontractors are required to adopt and comply with the requirements stated.
	Healthy materials	3	Toxicity of material has been considered prior to use. Particular impact of materials has been considered for either manufacturer's construction workers or occupiers. For instance, since underground construction has a dusty environment, dust filtration and collection are considered.
(C_5) Water	**Water pollution**	3	There is a water management in place. The main focus is to protect water resources (above and below ground) from pollution. An integral part of this initiative looks at conservation of water.

	Water resources	3	Construction water is the mains water with one exception: for the UUS Thames tunnel, for which a slurry tunnel-boring machine has been used. This uses UUS water resources (i.e. local groundwater extraction). This has dual benefits due to the rising groundwater levels that exist in the London area as a result of the cessation of pumping in some areas.
	Wastewater treatment and disposal	3	There is no need for wastewater management as there is a minimum waste. Water use is very low meaning not much wastewater is produced.
	Water monitoring	3	Meter and sub meters have been installed for water use monitoring for the operation stage. Water monitoring has been considered in building management and environmental systems. It is planned to minimise water loss and also sensors are in place to alert for any leakage that occurs.
	Water supply	3	Farringdon Station has been designed to maximise use of local, sustainable, low energy, water resources. As part of CRL projects, the design aims to minimise potable water consumption and as such initiatives are being developed onsite to reduce water use and to reduce the water footprint of Farringdon Station.
	Construction	3	Construction water is provided from Thames water. Greywater has been used throughout construction above and below ground, and a sustainable yield rate (i.e. not impacting on the river) has been determined.
(C_6) Energy	**Energy supply**	3	Energy savings will be maximised during the procurement process to reduce the carbon footprint and embodied energy of equipment and materials utilised during the project. These savings and considerations are documented in the Procurement Plan and will also form part of the Energy Management Plan. This energy management plan will identify and implement energy efficiency measures, as well as setting out legal and contractual energy requirements. It is endeavoured where possible to procure Green electricity from a suitably accredited supplier.
	Energy conservation and efficiency	3	The project considered reducing overall energy demand through LED lighting or switching lighting on and off using a sensor system. Operational efficiency of the project has been a key consideration during design.
	Energy monitoring	3	The Energy Management Plan details the methodology for data capture, monitoring and reporting under the Carbon Commitment Scheme and the following contract requirements regarding the monitoring and reporting of CO_2 and energy arising from transport to and from worksites. Energy has been monitored through a management system and meters and sub meters are installed for targeted energy. Also there are plans in place (and in use) for continual energy reduction.

	Day lighting	3	Day lighting has been problematic in UUS aspects of the site and as such is only available on the ground floor. Different options like fibre optics to get below ground have been explored; however, space requirements restricted adoption within the project. The same argument was given for sun pipes.
(C_7) Climate change	**Carbon management plan**	3	There is a carbon management policy which flows down to the requirements for the design specifications for this station, so there are requirements for designers to design reducing carbon and energy usage. Furthermore, when the contractor takes up the project again there is focus on reducing energy consumption in infrastructure and reducing energy consumption during construction and actual construction techniques. For the construction element, contractors are required to develop an energy management plan, which requires them to consider energy use in construction equipment as well as embodied carbon and they are required to demonstrate that they are reducing energy consumption constantly.
	Social impact of climate change	3	The project has considered the 120-year impact of climate change on communities; mitigation has been considered to allow the project to adapt to likely effects.
	Physical impacts of climate change	3	As a long-term infrastructure asset, potential impacts of climate change on the project and local built and natural environments have been identified for 120 years and the likely effects have been considered. A flood risk assessment has been carried out and the project has been designed to be flexible and withstand changes in case of changing climate over time. Future flexibility has been factored into the design where possible, particularly with regard to water levels, flood risk and higher ambient temperature.
	Economics of climate change	3	Consideration has been given to potential impact of climate change on the local economy and potential adverse effects have been mitigated. Such as …
(C_8) Air quality	**Ambient air quality**	3	The overall air quality within the station has been considered. Ground source heat pump in the form of the pipes has been used around the site. Trains are guarded by the door, so as soon as it arrives, it extracts and pumps the heat outside and then the door opens, it aims to exclude 90% of the produced heat.
	Direct emissions	3	Direct emissions produced from trains and vehicles used underground have been measured and solutions have been provided.
	Indirect emissions	3	Relevant studies on indirect emissions produced from trains and vehicles used underground have been done and remediation have been provided.

Table 6.1b: Social pillar assessment and scoring for Farringdon Station

Core indicators	Sub- indicators	Score	Justification
(C_9) Community facilities	**Recreation**	3	For the Farringdon Station, there is a community investment plan based on an understanding of what the community needs, and it brings opportunity very much tailored according to the findings. The location of the station is in a very dense area, and therefore, for the people living in these suburban areas, Farringdon Station provides the opportunity for easy transportation and connection to the facilities around the area.
	Education	2	Education does not apply directly to this specific project; however, Farringdon Station is located in a densely built area and it provides opportunity for better connection to surrounding educational institutions.
	Healthcare	1	It is not a directly applied indicator; however, due to the location of the station it provides a good access point to the healthcare systems located nearby.
	Retail	2	There are many retail shops around the station. Therefore, the station provides easier connection to the surrounding shops in the area.
(C_{10}) Culture	**Cultural and religious facilities**	1	This is not a directly relevant indicator applied to Farringdon.
	Use of environment	2	Throughout the planning process, one aim has been that the external appearance reflects the nature of the area so the station building has been designed in a way to reflect local architectural styles and craft.
	Archaeology and local heritage	3	An Archaeological Management Plan has been developed. This identifies and outlines management of the legal and contractual requirements for each work area, in order to avoid disturbance, and mitigates the impacts where disturbance is unavoidable. It also details how the archaeological contractor will be supported in his work. This will include excavation and removal of spoil where necessary, enabling access where required, and modifying working methods to enable watching briefs to be carried out. Where unexpected items are uncovered, work will cease immediately and the Crossrail Project Manager will be informed. As well as this, a Heritage Management Plan has been developed and will be implemented. Best practice mitigation measures detailed in this plan will be incorporated into construction method statements.
	Art	2	Huge number of art projects has been used to make the area looking more attractive. Even street artists have been engaged to make the area more calm and attractive.
(C_{11}) Form and space	**Density, scale and depth**	3	Located in densely urban populated areas the size of the station responds to the local spatial constraints. Crossrail has been working with architects to integrate the station building into the surrounding area.

	Public, private and communal space	3	Station entrance is unique, there is a clear definition and transition between public and private areas and entrances are clearly visible and private areas are screened to prevent public access. Above station is above ground which is a mixed use of commercial and residential areas.
	Security	3	Security has been a key consideration for Farringdon Station. Station will be controlled with 24 hrs CCTV. No one can get into station without ticket and clear signs for public and private places are provided.
	Connectivity	3	The main purpose of the station is providing a better connection and bringing community together. This will be achieved by easier and faster connection between Thameslink and better access to retails shops and facilities around the site.
(C_{12}) Stakeholder engagement	**Identification and analysis**	3	In the initial stages of the project all stakeholders were identified and communication have been started.
	Engagement process and feedback	3	Throughout the project, it has been ensured meetings were held regularly to engage all of stakeholders and feedbacks were integrated.
	Integrating stakeholder comments	3	The feedback and comments from meeting with stakeholders were documented and considered in the project.
(C_{13}) Health and wellbeing	**Access to green space**	2	There is no direct link between green areas and the station, as a way of conserving biodiversity provides no green areas. However, for the nearby stations such as Paddington, there is a green roof, which is not accessible by public but it improves health and wellbeing. However, there is no planned access to the surroundings green spaces.
	Community cohesion	3	Farringdon Station will bring community together by providing a better linkage to the adjacent community through transportation and connection. Travelling to Central London will be easier and potentially will reduce the tension over competition such as housing. It is also accessible for all groups of people e.g. disabled groups
	Institutions and social networks	3	For the station, it is aimed to lessen the impact and disconnection with social networks, for instance, by providing Wi-Fi in the underground station.
	Indoor environment	3	Indoor environment has been designed to be pleasant for people and through segregation of train, noise will be reduced greatly, shops and retails store has been provided as well as implementing art.
	Social vibrancy	2	It has been tried to provide facilities for all different group of society and to help o bring them together. However, there is no specific plan for that.
(C_{14}) Transport	**Public transport infrastructure**	3	The case study itself is public transportation itself and it is located in a well-needed area. It is planned that Farringdon will become one of busiest train stations and the main driver is providing an easy link for people located in outer London to the city and canary wharf. For example, about 140 trains per hour will flow through the Farringdon interchange when it becomes a link between Thameslink, Crossrail and London Underground services.

			Farringdon will be the only station from which passengers will be able to access all three networks (City of London Corporation, 2015).
	Pedestrian design and facilities	2	Walking ways are provided with adequate safety and enough lighting. However, no special facilities have been provided.
	Cycle design and facilities	2	No special facility is provided however, additional cycle parking is on the site.
	Water transportation	3	Water has been used to transform excavated material and has been significantly effective in reducing lorry journeys in the streets of London.
	Freight traffic	3	There is a management policy within Crossrail to reduce road transport for the station and make the most of the other methods such as the increasing use of rail freight by taking lorries off the roads hence leasing to les traffic congestion and carbon emissions.
	Private Vehicle use	3	Currently, there is no private vehicle use in underground space, however there is a plan if there will be in the future to encourage people to use low emissions of alternative fuels. There are policies and plans on the assessment of impact of private vehicle use.
	Low emission vehicles	3	Vehicles used underground such as technical machines have been all based on defined regulations and they are all regularly checked to make sure they do not bring any harm and they do not impact the produced CO_2.
	Air travel	3	The station now connects to the London Heathrow airport which means it is facilitating the ease of air travel.

Table 6.1c: Economic pillar assessment and scoring for Farringdon Station

Core indicators	Sub- indicators	Score	Justification
(C_{15}) Facilities management	Usability	3	A wide range of users/occupiers have been considered and tested where appropriate and data has been produced in the project report. These include pedestrians and other members of the public, and each design has considered people with low visual acuity or hearing problems, taking into account businesses or people travelling from either east or west. A Reliability, Accessibility, Maintainability and Sustainability (RAMS) analysis has been done for each and every equipment that has been used during the design stage.
	Appropriate technologies	3	There are not many new technologies specially designed for Farringdon Station. However, training and the establishment of a Tunnelling and Underground Construction Academy is a key element for Crossrail's plans.
	Whole-life flexibility	3	The project has been designed to last for 120 years and has been designed to withstand changes such as environmental ones. Since it is in a flooding area, water proofing structures and minimum water seepages are initial considerations.
	Operation and maintenance	3	As a part of the Crossrail Act, the maintenance and operation requirements of the projects have been identified and costed. Different stations are operated by Crossrail or TFL etc., to which responsibilities are assigned. A long term, 140-year maintenance plan has been considered.
(C16) Governance and reporting	Monitoring and evaluation	3	A comprehensive set of performance indicators such as cost, schedule and quality covering the project's key area are in place and they are assigned to the project manager and programme director. Meetings are held regularly to make sure it meets the needs of the various stakeholders.
	Information disclosure and reporting	3	Crossrail is committed to Local Government Transparency Code 2015 on data distribution. The data on policy decisions will be available to the public on the website. All data are available in a format that could be re-used, for example for research activities. Where any copyright concerns exist with the data it is stated clearly.
	Strategy	3	There is a sustainability strategy and management plan in place: responsibility and actions are all defined and all relevant financial incentives are funded.
	Risk management	3	Risk assessment ISO9001 is in place and all the risks and responsibilities have been assigned. All different categories of risk: financial, political and economic, have been identified and a risk management framework has been used.

	Donations to voluntary and community organisations	3	Crossrail is committed to participating in local communities. This could be through opportunities that arise from the construction programme. Community investment plans include the form of a donation of skills, time, money and expertise to help bring long-term benefits to the local communities where Crossrail contractors work.
(C_{17}) Economic effect	**Value for money**	3	Value for money is a key part of the economic performance of the project. There is a detailed understanding of the costs and benefits associated with the project over its entire lifecycle. Long term benefits and impacts of non-monetary costs have been considered and alternative solutions for positional operational savings have been calculated.
	Distortions to local economy	3	The project does not present potential negative impacts, whilst it even brings benefits and improves local economy and businesses. This is part of their commitment plan and there is a programme to relocate damaged utility works. Overall impact of expected damages has been calculated and there are some strategies in place to mitigate the potential negative impacts on such occasions.
	Vitality and regeneration	3	It has been aimed to consider local industries through the project, for example for the required materials. There is a plan to link to the market opportunities and promote employment, for example by going to schools encouraging and promoting engineering or holding exhibitions. It is planned to promote sustainable businesses, for example by promoting roof gardens on the west end of the project.
	Carbon pricing	3	Calculations have been done and they have shown that retaining some of the existing façade and part of the frame saved over 3,000 tonnes of CO_2e.
(C_{18}) Employment and skills	**Labour standards**	3	Enough wages are provided to those involved in the project for at least a basic standard of living. There are health and safety programmes in workplaces including drug and alcohol tests, health checks and a cancer awareness programme. All the materials are CE marked (i.e. they fit the regulation regarding health and safety or environmental protection) and suppliers are approved by UK accreditors, which mean they all have the minimum requirement of standards.
	Training	3	It has been ensured that all staffs have received environmental awareness training within 6 months of joining the project. For example, some tunnelling design and maintenance has been done and, to fulfil the shortfall in local capacity to maintain and operate the project, one of the actions Farringdon took was holding training sessions for people from school and offering employment later. Local services have been used in some cases for training purposes, such as concrete mixing.

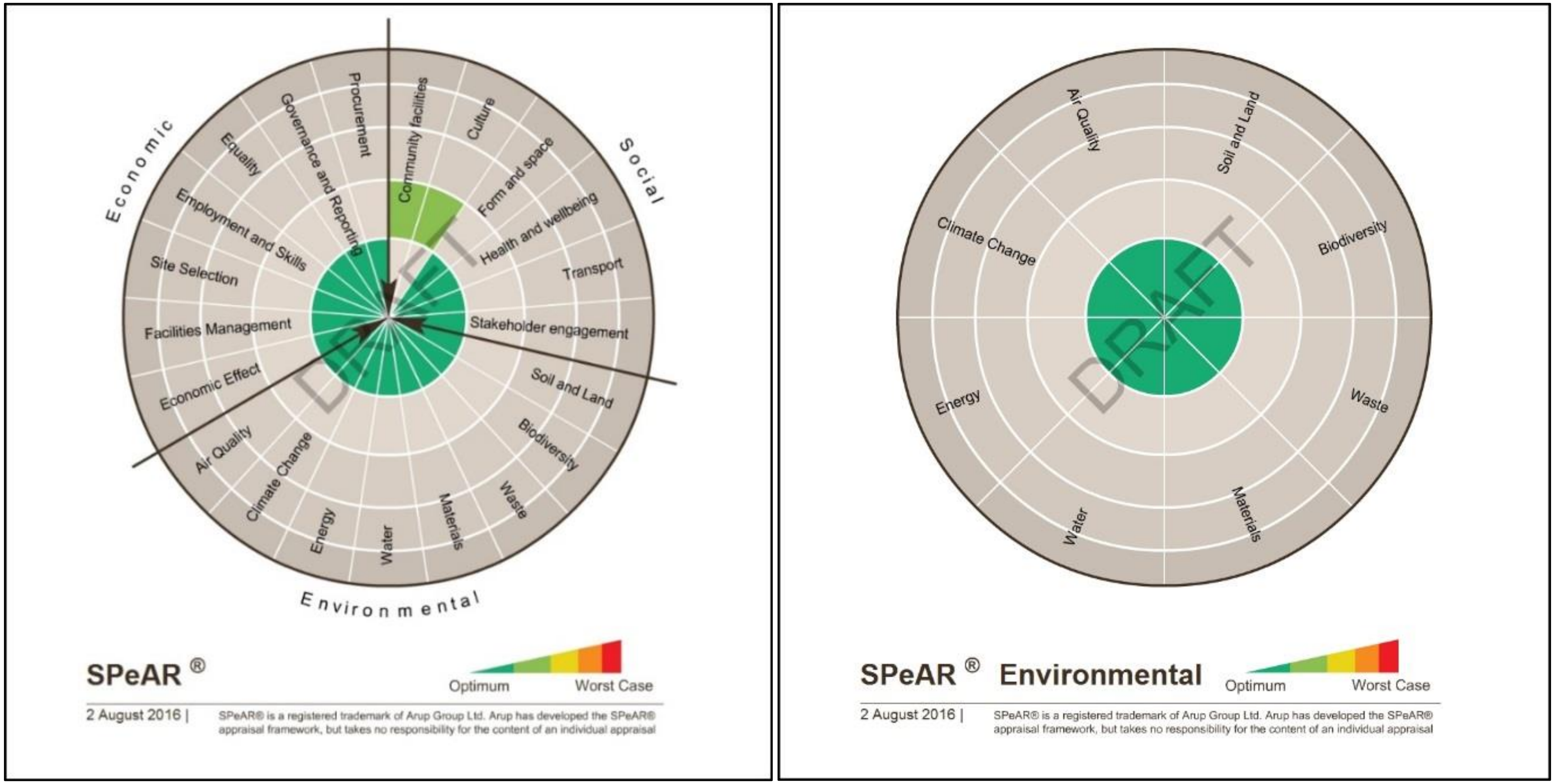
	Access to finance	3	The whole Crossrail project is requested to recognise the importance of promptly cascading money down through the supply chain and act accordingly.
	Employment creation in construction	3	There is not any prioritisation over labour-based employment rather than technology, as there are health and safety checks. Job opportunities are advertised for 28 days, which provides enough time to apply. Jobs offered are long-term (2+ years), can continue till 2019, and there is opportunity for local people to benefit from employment.
	Employment creation in operation	3	The number of jobs to be created during the operation of satiation has been estimated and positions will be advertised. There is opportunity for local people and the jobs are offered long term.
	Social mobility	3	As part of Crossrail there is a strategic Labour Needs and Training programme that aims to address skills shortages in key areas in line with London's socio-economic challenges, along with providing a supply of skilled workforce and managers for future projects.
Site selection (C_{19})	**Site location**	3	This has been a fundamental consideration for the project. It is totally accessible for different groups of people. There has been initial assessment for opportunities that the project can provide and ways to minimise any negative impacts.
	Planning intent	3	With respect to Farringdon Station, relevant investigations with regard to planning intent and compliance with regional/local planning were done in the early stages of the project.
	Diversity / mixed use	3	In the station there is an entrance, the 'paid site', which people can go through a barrier to access, and another part concerned with retail facilities. There is therefore a diversity of facilities in the area. Mixed use of the area is based on local needs, contributes to the surrounding diversity, and is accessible to all local residents.
Procurement (C_{20})	**Local sourcing**	3	Local availability of materials has been considered during design and has been checked against project specific requirements. Construction/supply chains have been analysed between source and end user to find the most appropriate supplier.
	Global sourcing	3	Global availability of materials has been considered during design and has been checked against project specific requirements. For some materials, there was opportunity to prioritise local suppliers; however, this was not the case for bulk materials.
	Procurement strategy	3	There is a project specific sustainable procurement strategy, which covers all design, construction and operational procurement function. The procurement strategy supports sustainability goals and targets and guidance with respect to the cost against other criteria is provided. The strategy has been rolled out to other members and training has been provided.

Equality (C_{21})	**Affordability**	3	The main purpose of the project is to provide an 'easy' transportation link, so it is designed for all groups of people from all socio-economic backgrounds.
	Designing for equality	3	During the construction period, there was an assessment of the adverse effect that implementation of the project could have on the different social groups, for example ethnic, religious. The assessment showed that there is no group that could be adversely affected during development and implementation. Plus, issues of disability and accessibility have been considered during construction and operation stages.
	Impacts and benefits	3	There was a social, economic and environmental impact assessment of the project and all stakeholders were included. Negative points have been identified and strategies and solution were found.
	Land tenure	3	Land tenure is resolved and clear.
	Displacement	3	Project impact on the nearby housing and offices were investigated at the beginning. The resulting influence will be reimbursed.

6.2.4 Farringdon Station's assessment findings; SPeAR® vs USPeAR

This section describes and compares SPeAR® and USPeAR assessment results for the Farringdon Station project. In the SPeAR®, indicators are considered of equal importance and the output is a graphical representation of the scoring, this can be used as an indication of weaknesses and strengths of the project. The Farringdon Station project, as previously mentioned, has been rated excellent in CEEQUAL, which means it complies to a great extent with sustainability. The SPeAR® results (Figure 6.7) are therefore another validation of Farringdon's excellent performance in terms of sustainability. As the graphs indicate, most indicators show up as 'exemplary'. The exceptions are 'community facilities' and 'culture' in the 'social' pillar, which are still scored as best case. Overall, Farringdon Station's performance has been exemplary and most criteria judged to be excellent. Following consultations with the Farringdon team and managers, for scoring the indicators, and assessing the station using the SPeAR®, the station was assessed using the newly developed USPeAR in order to demonstrate the performance of the station with the allocated weighting. The results of USPeAR assessment are presented in the form of graph (Figure 6.8).

Within the USPeAR assessment, the scoring results are same as SPeAR®, demonstrating once more that the project has been excellent with respect to all sustainability criteria. Most criteria fall into the green area and it presents the best possible results. However, the assessment results in Figure 6.8 show the current state of the environment, society and economy with the difference of considering weighting in each indicator's segment. This leads to identifying the most important criteria. For example, with respect to Farringdon Station, as it has also been demonstrated in SPeAR®, the only indicators that are not exemplary are 'community facilities' and 'culture'. The weighting and relative importance of these indicators as shown in USPeAR is 1.195 and 1.23 respectively.



Economic
Social
Environmental
Procurement
Governance and Reporting
Equality
Employment and Skills
Site Selection
Facilities Management
Economic Effect
Air Quality
Climate Change
Energy
Water
Materials
Waste
Biodiversity
Soil and Land
Stakeholder engagement
Transport
Health and wellbeing
Form and space
Culture
Community facilities
DRAFT
SPeAR ®
Optimum
Worst Case
2 August 2016 |
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Air Quality
Soil and Land
Climate Change
Biodiversity
Energy
Waste
Water
Materials
DRAFT
SPeAR ® Environmental
Optimum
Worst Case
2 August 2016 |
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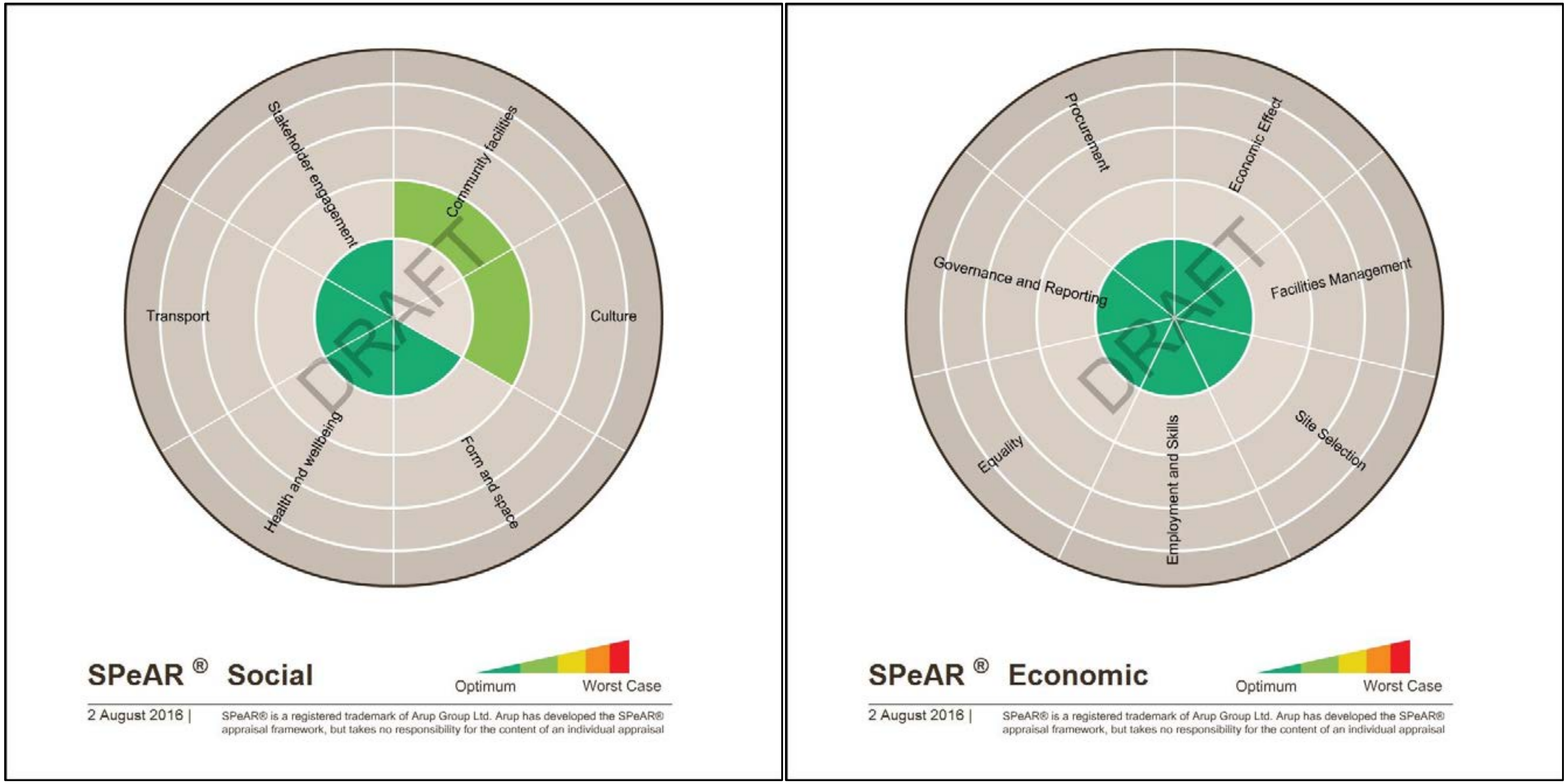
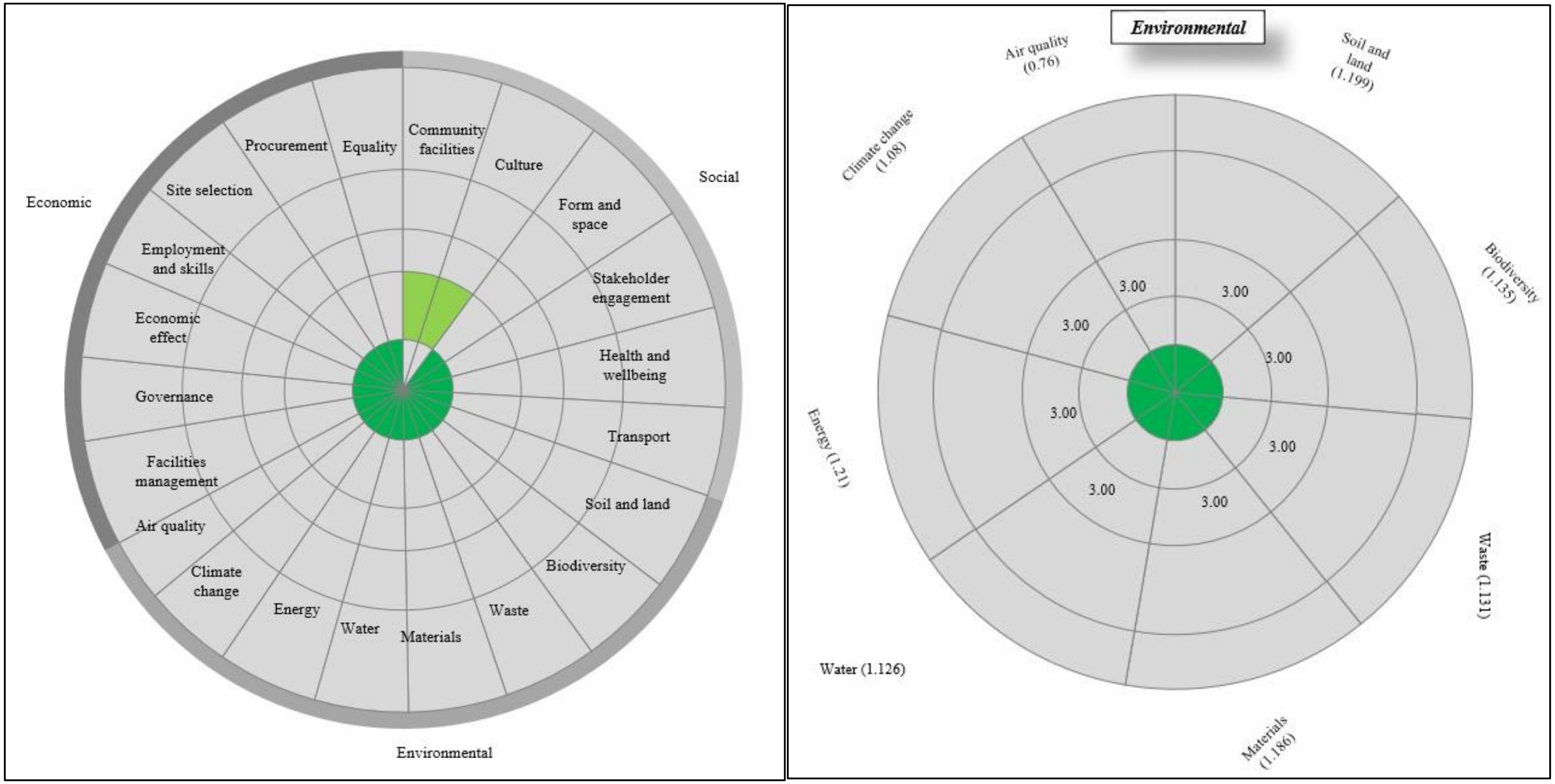
(a)



(b)

Figure 6.7: SPeAR® results for Farringdon Station, (a) overall score and environmental pillar (b) social and economic pillars


Economic
Social
Environmental
Procurement
Equality
Community facilities
Culture
Form and space
Stakeholder engagement
Health and wellbeing
Transport
Soil and land
Biodiversity
Waste
Materials
Water
Energy
Climate change
Air quality
Facilities management
Governance
Economic effect
Employment and skills
Site selection
Environmental
Air quality (0.76)
Soil and land (1.199)
Biodiversity (1.135)
Waste (1.131)
Materials (1.186)
Water (1.126)
Energy (1.21)
Climate change (1.08)
3.00
3.00
3.00
3.00
3.00
3.00
3.00
3.00

(a)

(b)

Figure 6.8: USPeAR results for Farringdon Station, (a) overall score and environmental pillar (b) social and economic pillars

6.2.4.2 Interpretation of the findings

USPeAR aims to help the decision maker to decide on how to improve the performance of the project, by identifying which indicators are worth improving upon based on their project goals. However, Farringdon Station is an exemplary case of sustainability. Indeed, it has shown that attaining excellence has always been their target, regardless of the importance / weighting of the indicators, and they considered all elements of sustainability goals with the same importance (i.e. weight). One of the key drivers behind the project's success was Thameslink programme's sustainable design and construction strategy, which set the targets and objectives of the project. The project team goal was to achieve a CEEQUAL "Excellent" award, which has actually happened. To mention a few examples, a couple of indicators performances will be analysed, and Farringdon Station's performance on these indicators will be discussed (the following information has been obtained from meetings with Farringdon's staff and references have provided where available).

"Energy" (W= 1.21); Energy is a highly weighted indicator. The existence of the energy management plan within Farringdon Station indicates a desire to seek ways to reduce energy use and the carbon footprint of the project, as outlined. It is targeting an 8% reduction in carbon associated with the project when compared with the baseline estimated during the project tender. The energy management plan will also detail the methodology for data capture, monitoring and reporting under the carbon commitment scheme, and the following contract requirements regarding the monitoring and reporting of CO_2 and energy arising from transport to and from worksites.

"Transportation" (W= 1.06); For example, although London has good public transportation facilities, congestion is still a significant problem at certain times on both road and rail. Thus, there is a need to expand the infrastructures to help minimise car use. A plan was made to facilitate connection, and emphasis is placed on discouraging unnecessary journeys whilst encouraging people to use public transport. Farringdon Station's construction has been a big step towards achieving this and it has been highly successful.

"Governance and reporting" (W= 1.003); For this purpose, there is specific environmental data reporting requirements which is reported to the Crossrail project manager on a four weekly basis using the agreed reporting template. Crossrail specific systems are also used to report incidents. Some of the environmental data requirements relate to the following areas:

• Energy consumption;

• Resource consumption;

• Waste produced and proportion recycled;

• Water consumption.

With respect to *"Employment and skills"* (W= 1.02), Farringdon Station directly employs station operators. Increased capacity of the new station will increase employment in the area. Last but not least, the *"Equality"* indicator: London has wide variety of national, ethnic and religious backgrounds (Kohli, 2015). However, Farringdon has attempted to bring equality with respect to access to services such as jobs and health services making them available for use for all members of the public. This spans much further than the station project itself.

Farringdon Station has been chosen as a model of excellent sustainability that can be used to benchmark an underground facility or project. The results of the application of the USPeAR tool can be compared against those obtained through CEEQUAL, which has been previously used to evaluate Farringdon Station, in order to provide a validation for the USPeAR tool. A second case study was undertaken, as described in the following section, to investigate how USPeAR could help a project to achieve sustainability goals as well as Farringdon Station.

6.3 Case study 2: Aghdasiyeh Station- Tehran

Iran is a country with a population of more than 75 million, mainly living in megacities including the capital Tehran, Mashhad, Isfahan, Tabriz and Shiraz. Megacities across Iran face rapid population growth and associated traffic congestion, which lead to increasing difficulties in pursuing normal daily activities (Realiran.org, 2015; Lalehpour, 2016). The population growth is mainly due to the job opportunities available in those megacities, promoting migration from smaller urban areas. Every day, millions travel between their home and workplace using either public or private transportation. The large number of people travelling during peak hours, including mornings, leads to traffic jams on the streets and highways. The ultimate results are long journey times (a huge irritation and cost for users), heavy air pollution and a huge increase in fuel consumption. Concerns over the air pollution led the Iranian government to develop and pursuit of public transport as the alternative more convenient and cheaper way for daily journeys. The new development involved constructing an underground transport system in Tehran and other megacities in Iran (Realiran.org, 2015). The Tehran underground, known as Metro, consists of four operational underground metro lines, a fifth over ground rail line, and a further two lines under construction, started in 2007

(Figure 6.9). The Tehran Metro carries more than 3 million passengers a day, with some 815 million trips being made on Tehran Metro in 2014 (Realiran.org, 2015). As of April 2014, the system was 152 km (94 miles) long, and it is planned to have a length of 430 km (270 miles) with nine lines, once all construction is completed by 2028 (Realiran.org, 2015).

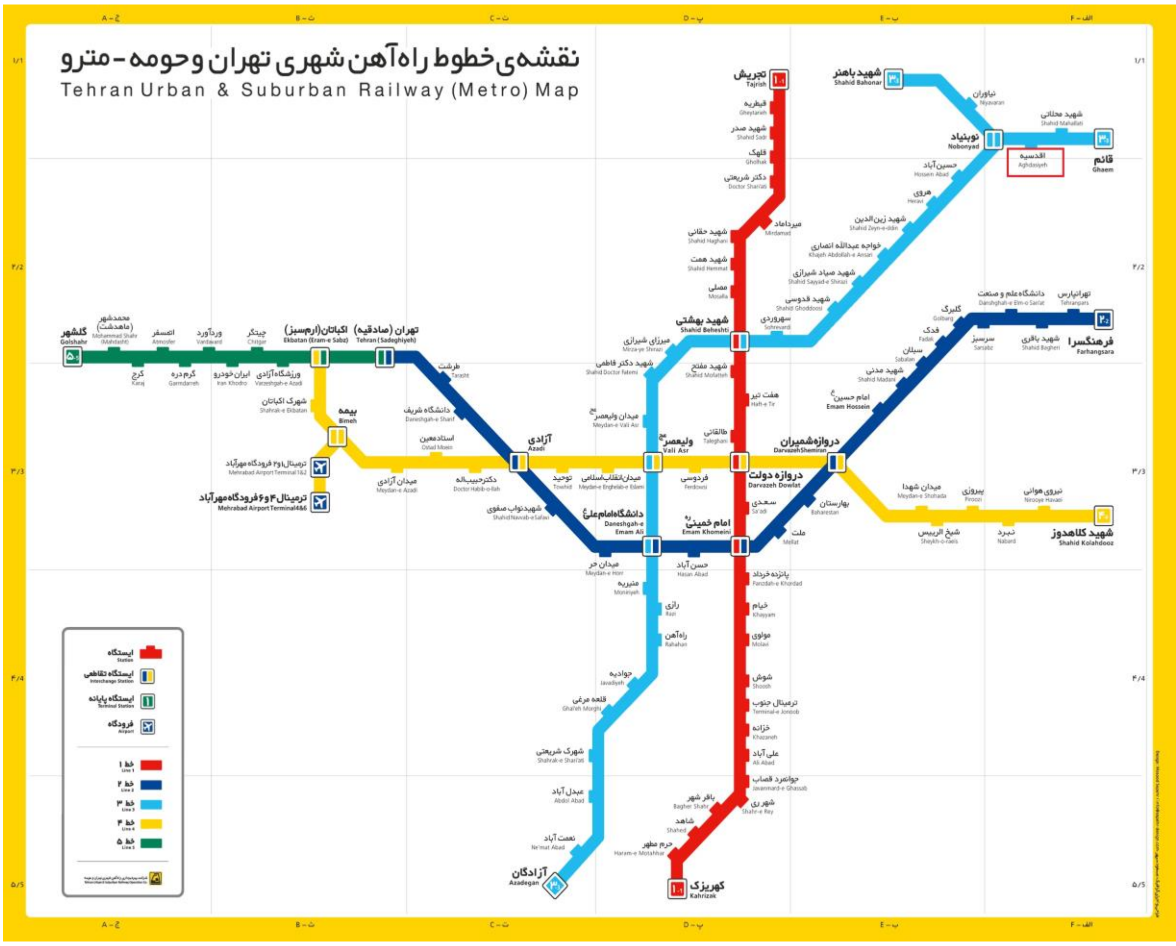


Figure 6.9: Tehran Metros' map (Tehran Urban & Suburban Railway Operation Co, 2016)

In this research Line 3 of the metro, Aghdasiyeh Station is used as the second case study. Line 3 of Tehran metro is the longest metro line in the Middle East, at 37 km in length (shown with blue colour Figure 6.9). Line 3 will ultimately comprise 28 stations, of which 12 are currently operational (Figure 6.10) (darabi et al., 2012).

(a) **(b)**

Figure 6.10: A snapshot of (a) ticket hall (b) tunnel of Aghdasiyeh Station

6.3.1 Scoring of Aghdasiyeh Station- Tehran

Discussions were piloted on the indicators through meetings held with staff team at Aghdasiyeh Station (details are given in Chapter 3, Section 3.4.2). Since Farringdon Station has been assessed previously using SPeAR®, and justification has been found for it to be used as a benchmark, the performance of Aghdasiyeh Station will be assessed against the ideal case of Farringdon. Each indicator was specifically assessed and performance determined. Similar to the previous case study, scorings of -1 to 3 were selected. During the meetings, indicators were assessed based on the guided questions given by SPeAR® and assessed by the team and scores were given. Details of the indicator analysis collected in the meetings are provided in Tables 6.2(a, b, c). The justifications provided in the tables are derived from explanations given in the meetings.

Table 6.2a: Environmental pillar assessment and scoring for Aghdasiyeh Station

Core indicator	Sub indicator	Score	Justification
(C_1) Soil and land	Contaminated land	3	Soil has been assessed regarding the land contamination, a report was prepared for that, and due consideration given.
	Soil quality	3	Soil has been tested prior to the project and the inappropriate soil was mostly removed.
	Drainage systems	0	There is no specific water management plan. Drainage is considered, but there was unpredicted water runoff which led to the submersion of machinery and damage.
(C_2) Biodiversity	Protected species and habitats	2	The station is located in a very dense area of the city so there are not many animal species around. Whilst there is ecological concern, which aims not to damage the more extensive species, there is no specific plan or action in place.
	Conserving and improving local biodiversity	1	It has not been a priority in the project and has not been considered and there is no specific plan or action regarding conserving and improving biodiversity.
(C_3) Waste	Construction waste management plan	1	There is a strategy for waste management. It is aimed to use recycled material where possible however, there are no specific goals regarding the waste management and it depends on the conditions and the ease of reuse.
	Waste in operation	2	The waste produced during construction is collected through bins and traditional methods.
	Hazardous/special waste	1	There is not much hazardous/special waste in Tehran, however consideration has been given in the case of encountering any. However, an action plan for so doing is missing.
	Designing out waste	2	There is a plan for dealing with waste during design stage however, no targets have been placed. It only includes ways to reduce or recycle waste.
(C_4) Materials	Materials efficiency in design	1	It is aimed to use the most efficient materials, which are mainly more cost effective, and where possible to reuse. However, it is only confined to the onsite-reused materials.
	Use of recycled or reused materials	1	Some recycled materials are used which is known before for example some soils. However unfortunately there is no specific management plan of how much of recycled material to use and there is no specific target for the use of recycled materials.
	Environmental and sustainability impacts of materials	2	Materials are very limited and specific, no variation for materials has been used/considered, and, there is no specific environmental and sustainability impact of materials provided.
	Healthy materials	2	Toxicity of material has been considered prior to use. Particular impact of materials has been considered for either manufacturer's construction workers or occupiers. However, there is no specific regulation to follow.

(C_5) Water	Water pollution	2	There is no specific water management plan however onsite consideration is given. The focus is to protect water resources (above and below ground) from pollution. An integral part of this initiative looks at conservation of water.
	Water resources	2	Construction water mainly for concrete is supplied from city mains water, which is bought, and the cost will be calculated. For the other purposes local groundwater are used.
	Wastewater treatment and disposal	1	No need for wastewater management was identified as there is a minimum waste. Water use is very low, meaning not much wastewater is produced.
	Water monitoring	1	Groundwater level is monitored and pumped if required. Leakage might happen and it might be fixed with lining. However there is no meter and sub meter for water usage.
	Water supply	1	For the station, the aim has been to use less potable water and maximise use of greywater. However, there has not been very much investigation into water supply.
	Construction	3	Construction water is mainly bought from companies, they provide water and greywater has been used as well.
(C_6) Energy	Energy supply	1	There is no energy management plan; the aim is to reduce energy consumption but there is no actual goal or targets, however consideration will be given.
	Energy conservation and efficiency	1	There is no specific target or plan for energy conservation. Alternatives such as LED lighting might be considered.
	Energy monitoring	1	There is no specific energy management plan, however it is aimed to minimise energy use but sub meters and meters are not provided and specific co_2 use are not measured.
	Day lighting	1	Day lighting has been problematic in UUS aspects; fibre optics has been used around the station and the aim was to use lighting with less energy use and more efficiency.
(C_7) Climate change	Carbon management plan	-1	There is no specific carbon management plan and carbon management has not been considered seriously.
	Social impact of climate change	-1	There is no specific plan or investigation into social impact of climate change.
	Physical impacts of climate change	2	As a long-term infrastructure asset, flood risk assessment was conducted and the mitigation measures were considered.
	Economics of climate change	2	Flood risk was considered and associated costs, for dealing with potential damages, were included in the maintenance budget.
(C_8) Air quality	Ambient air quality	2	Air quality of station is aimed to be controlled, there is fan and ventilation system all over the station to make sure the air is ventilated regularly. However, there is no other specific action to monitor this.

	Direct emissions	2	Direct emissions associated with the machines and trains have been considered and ventilations have been provided.
	Indirect emissions	1	Indirect emissions from machines and trains underground have been investigated however, mitigations and plans are not provided.

Table 6.2b: Social pillar assessment and scoring for Aghdasiyeh Station

Core indicator	Sub indicator	Score	Justification
(C_9) Community facilities	Recreation	3	The location of the station is in a very dense area and it is located in close proximity to public amenities. Therefore, considering the traffic in the city and for the people, station provides the opportunity for easy transportation and connection to the facilities around the area.
	Education	2	There are several schools located nearby the stations, and stations opening provides opportunity for easier transportation.
	Healthcare	0	It is not a direct reflection of the station design, and there is no specific healthcare located nearby. However, it could be used as a way of transportation to get to the nearest hospital.
	Retail	3	The station itself is a part of large complex and shopping centres which is under construction. However there are many retail shops all around the station. In addition, there are a few shopping centres located in close proximity. Therefore, the station provides easier connection to the surrounding shops in the area and it aims to reduce congestion on the surface.
(C_{10}) Culture	Cultural and religious facilities	3	Station and facilities are available to all different cultural and religious groups, while there is no differentiation between different groups and cultures. For example, a praying room has been provided for people in the station.
	Use of environment	2	Consideration has been given to the existing environmental features and relevant studies and investigations have been done. For example for the line 3, where there was a spring passing through the ground, all consideration was given to make sure it was not disrupted.
	Archaeology and local heritage	3	Subway construction has been aligned with cultural heritage organisations of Iran; nearby heritage sites have been identified. There was no archaeology or heritage sites nearby, therefore there is no specific action planned.
	Art	2	Placing arts around the station have been a part of the plan and arts have been used to make station a more pleasant area.
(C_{11}) Form and space	Density, scale and depth	1	Some studies relevant to density and scale and depth have been done and some changes have been undertaken due to the studies and investigation. However, there was no specific plan or action, and it was just a matter of decision at the time.
	Public, private and communal space	3	Within the station there is a clear definition of the areas (public, private and communal spaces and adequate signs are provided).

	Security	3	Security of station has been considered. CCTVs have been provided all around the station. Security guards are available on the site as long as the station is open and no one is allowed to get to the station without ticket.
	Connectivity	3	The station location is in a very dense area and it is very well needed in the area. The main purpose is to provide better connections to different parts of the city, which is almost impossible on the surface due to traffic congestion. Line 3 is one of the most important lines as it connects southwest Tehran to northeast, and crosses busy parts of the capital city (Irna.ir, 2015).
(C_{12}) Stakeholder engagement	Identification and analysis	3	In the early stages, the stakeholders were identified clearly.
	Stakeholders participation and consultation	3	Meetings have been held regularly between stakeholders. In addition, stakeholders were involved and there has been regular commination between them.
	Integrating stakeholders comments	3	Stakeholder comments have been considered and ultimately integrated along the way of the project.
(C_{13}) Health and wellbeing	Access to green space	3	Station has brought great opportunity to the area, since there is a park nearby. Through use of the station, the transportation to the park will be much easier and in a shorter travel time without the necessity of travelling on the surface.
	Community cohesion	3	There is a park nearby the station, which has a recreation centre, and there is a gym swimming facilities and restaurant. It offers a good opportunity for bringing community together.
	Institutions and social networks	1	There is no specific plan regarding this, however it has been tried to make sure there is a good mobile phone signal and therefore users internet phone works.
	Indoor environment	2	Indoor environment has been designed in an ideal way for the passengers, a friendly environment with café has been provided. There are small shops areas, designed to provide refreshments.
	Social vibrancy	2	It is aimed to bring different group of society together by providing different attractions such as arts or café and small shops.
(C_{14}) Transport	Public transport infrastructure	3	The project itself is a public transportation. It is located in a very populated area. It is planned to carry a large number of population from all around the city and reduce congestion on the surface.
	Pedestrian design and facilities	3	There are appropriate corridors designed for the pedestrians and signs and lighting have been designed for that.
	Cycle design and facilities	1	No special facility has been provided. However, there is space to park the bike and there is facility for the passenger to take it to the train with themselves.
	Waterways	0	There is no waterway around the station therefore, it has not been used and there is no policy about that.

	Freight traffic	-1	Unfortunately, there was not any policy or plan to reduce road transport or using alternative ways of transport for the station.
	Low emission vehicles	-1	Unfortunately, even for the machines used underground there is no specific regulations for their emissions and there is no rule or plan to check or monitor them. This sometime has led to the serious illness of the staff due to not providing appropriate working environment. Ventilation has been used in the tunnels to prevent this, but often this is not enough.
	Private Vehicle use	-1	There is a plan for providing an underground car park near the station however unfortunately there is no plan for controlling the emissions or encouraging the use of low emission vehicles or vehicles with alternative fuels.
	Air travel	-1	Unfortunately, the station does not facilitate air travel and even does not connect to any airports.

Table 6.2c: Economic pillar assessment and scoring for Aghdasiyeh Station

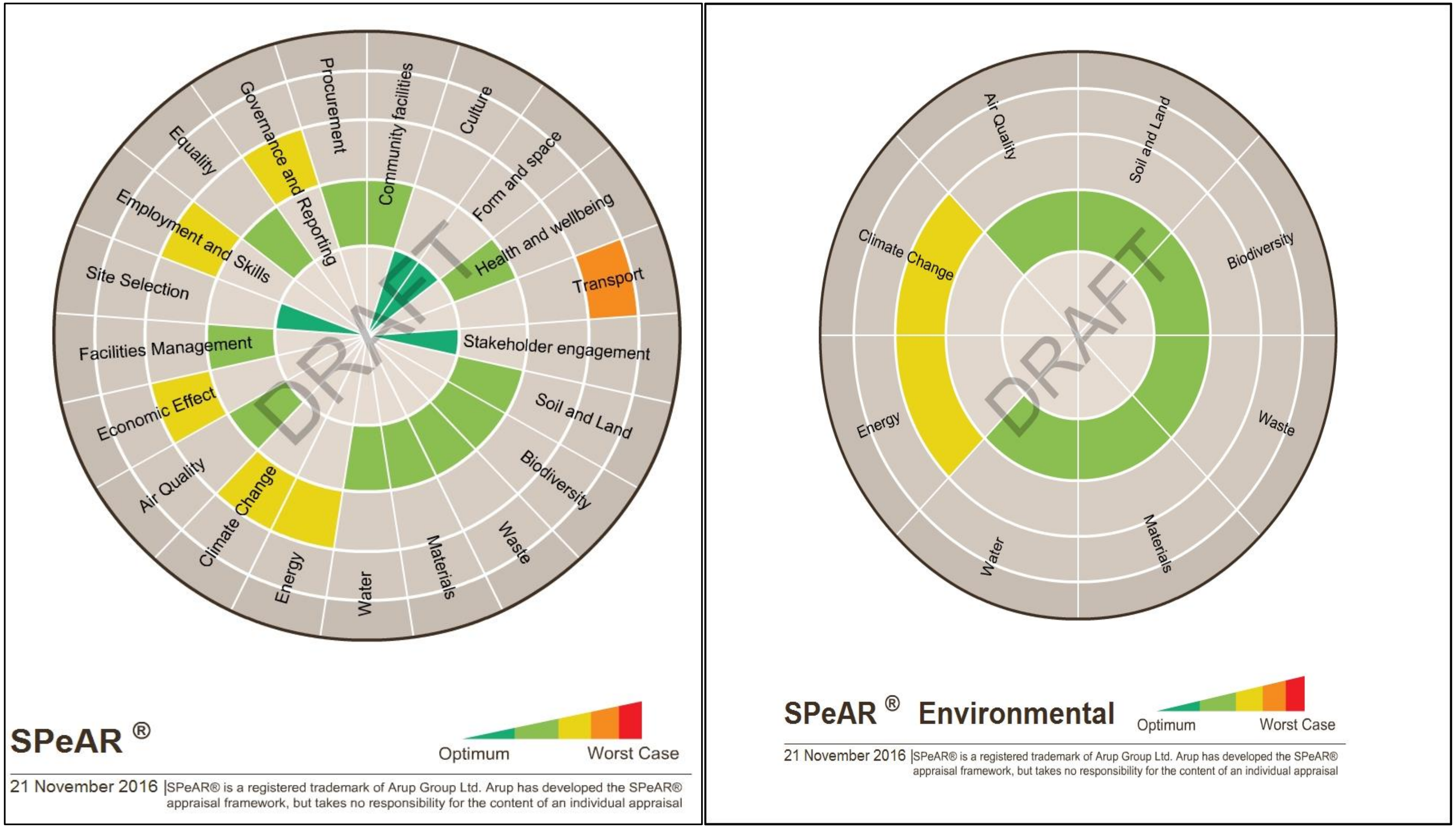
Core indicators	Sub indicators	Score	Justification
(C_{15}) Facilities management	Usability	2	A range of users was accounted for including pedestrians, cyclists and people with disability. However, there is no specific plan or measures for people with low visual acuity or hearing problems.
	Appropriate technologies	3	For all the designed technologies within the station, in terms of facilities management, staff training has been done and guidelines have been provided for the longer-term use. Adequate facilities have been provided.
	Whole-life flexibility	2	There is no specific timeframe for the design of the project. However, it is designed to be flexible with future changes. For example, since Tehran is located in seismic places, it is designed to withstand a scale 8 Richter earthquake.
	Operation and maintenance	2	As a part of the metro management policy, the maintenance and operation requirements of the projects have been identified and relevant solutions have been provided.
(C_{16}) Governance and reporting	Monitoring and evaluation	2	A set of key indicators such as cost and quality have been designed and checked regularly and ultimate costs have been determined too.
	Information disclosure and reporting	0	Some data are available on Metro's website on some general information such as boreholes. However more detailed data is not accessible.
	Strategy	2	There is a sustainability strategy and management plan in place: responsibility and actions are all defined and all relevant financial incentives are funded.
	Risk management	3	Risk assessments have been done and there is a risk management plan in place. The main criteria are against time and cost, for example the impact of change in cost of materials.
	Donations to voluntary and community organisations	-1	There is no specific plan for donations to other organisations. The main reason is that the budget for the station itself is very low and construction is often stopped due to the lack of financial resources.
(C_{17}) Economic effect	Value for money	2	A key element of the project is the benefit it is providing in terms of the economy. There is a detailed understanding of the costs and benefits associated with the project over its entire lifecycle. It will be investigated how the project contributes to fuel consumption, pollution and quality of life, in particular less congestion, and to reduction of trips taken with private vehicles and overall economic benefit.

	Distortions to local economy	1	The project does not present potential negative impacts and it even brings benefits and improves local economy and businesses. However, there might be noise and limited access during construction. After construction, there might not be enough car parking around the station to deal with the presence of huge number of taxis. The lack of a proper plan or management is evident.
	Vitality and regeneration	1	This has not been studied or investigated however the project is located in a well-needed area, this should help regarding the regeneration of the area.
	Carbon pricing	-1	There is no carbon management plan and consideration to carbon and its associated impacts have not been considered at all.
(C_{18}) Employment and skills	Labour standards	1	Wages are provided in such a way as to ensure a basic standard of life. There is HSE on site to check on labour health and safety, drug and alcohol tests and cancer awareness. However this has not been done properly and there are serious risks to staff health due to the air conditions within the under construction tunnel.
	Employment creation in construction	2	There is not any prioritisation over labour-based employment rather than technology, as there are health and safety checks. Job opportunities however will be created. With construction of each line of the metro 16,000 direct job and 165,000 indirect job will be created.
	Employment creation in operation	2	There are a number of jobs created during the operation for maintenance and running the metro station. However there is no estimation on that so far.
	Training	1	It is aimed to train all the staff according to HSE regulation will be taught to all staff for both construction and operation stage however there is no specific plan for that.
	Access to finance	0	The financial situation is very challenging. The project has been delayed due to inadequate capital.
	Social mobility	1	There is a possibility for different social groups to be employed and improve their situation financially. However, it is first come first served, and no special training will be provided.
Site selection (C_{19})	Site location	3	A key element for this station was the site location. For a long time, there has been traffic congestion on the surface in this location where people were travelling there for different purposes. It is estimated that a large number of people will be travelling by metro daily.
	Planning intent	2	Relevant investigations with regard to planning intent and compliance with regional/local planning were considered in the initial stages of the project, however there were some conflict, which have been resolved.
	Diversity / mixed use	3	As a part of the station, there will be a shopping centre "Atlas Mall". In addition, there will be a park and recreation facilities nearby the station. Therefore, there will be a mixed of facilities provided by the station.

Procurement (C_{20})	Local sourcing /	2	Most suppliers are Iranian. Even wagons are prepared locally and there is a plan for local sourcing of the material.
	Global sourcing	2	There is some global sourcing for materials as well, such as lifts; they are identified and planned for.
	Procurement strategy	1	This is mostly focused on the project time frame, based on design. There is a guideline and procurement strategy on what are needed and who is responsible for. However, it is not always done based on the plan.
Equality (C21)	Affordability	3	The project purpose is to ease transportation and reduce surface congestion. It is designed to be used for everyone and be affordable. For example, ticket prices are affordable and there is opportunity for free public transport to be provided to people with disabilities and students in schools with special needs.
	Designing for equality	3	There has not been a specific assessment of the adverse effect that implementation of the project could have on the different social groups, for example, ethnic and religious. This has not been mainly considered. However, it is believed that there is no group that could be adversely affected during development and implementation. In addition, issues of disability and accessibility have been considered during construction and operation stages.
	Impacts and benefits	2	There has been a social, economic and environmental impact assessment of the project and all stakeholders were involved. Negative points have been identified and strategies and solution were found.
	Land tenure	2	There are some land ownership issues within this line. However, for this station land ownership is resolved and clear.
	Displacement	0	There is no specific plan for the displacement to the nearby housing or infrastructures. However, if any damage occurs, those affected would be reimbursed.

6.3.2 Aghdasiyeh Station's assessment findings; SPeAR® vs USPeAR

The following sections describe the finding of SPeAR® and USPeAR tool when applied to Aghdasiyeh Station The result of the assessment undertaking by SPeAR® is presented in Figure 6.11, which shows the overall performance of the project and the results of three pillars of environment, social factors and economy. The graphs represent the weaknesses, areas that could be improved and strength points of the project. Based on the results, there is no indicator identified as 'worst' or in red zone. The weakest point is 'transport' which lie within the orange zone or minimum standard. ‘employment and skills’, ‘economic effect’, ‘governance and reporting’, ‘climate change’ and ‘energy’ appear within the yellow zone or ‘good practice’ in the graph. The rest of the indicators belong to the green zone, the best practice or exemplary area. Based on the results obtained from the SPeAR® at this stage, indicators of ‘stakeholder engagement’, ‘form and space’, ‘culture and procurement’ are exemplary, however the rest of the indicators show that the project can be improved significantly. Therefore, most of the indicators have the potential to be improved. The one that was scored worst, and therefore requires extra care is ‘transport’. The main reason behind the poor performance of the transportation aspect of the project is the fact that there are not enough car/bike parking facilities nearby and not enough trains are provided for the large number of people using the station hence the waiting times are long and station is crowded. This could be a key finding of the case study and a major concern, as the project itself concerns facilitating improved transportation. When improving the project, ultimately transportation will have an ultimate effect on other indicators as well.



Procurement
Community facilities
Culture
Form and space
Health and wellbeing
Transport
Stakeholder engagement
Soil and Land
Biodiversity
Waste
Materials
Water
Energy
Climate Change
Air Quality
Economic Effect
Facilities Management
Site Selection
Employment and Skills
Equality
Governance and Reporting
DRAFT
SPeAR ®
Optimum
Worst Case
21 November 2016 | SPeAR® is a registered trademark of Arup Group Ltd. Arup has developed the SPeAR® appraisal framework, but takes no responsibility for the content of an individual appraisal
Air Quality
Soil and Land
Biodiversity
Waste
Materials
Water
Energy
Climate Change
DRAFT
SPeAR ® Environmental
Optimum
Worst Case
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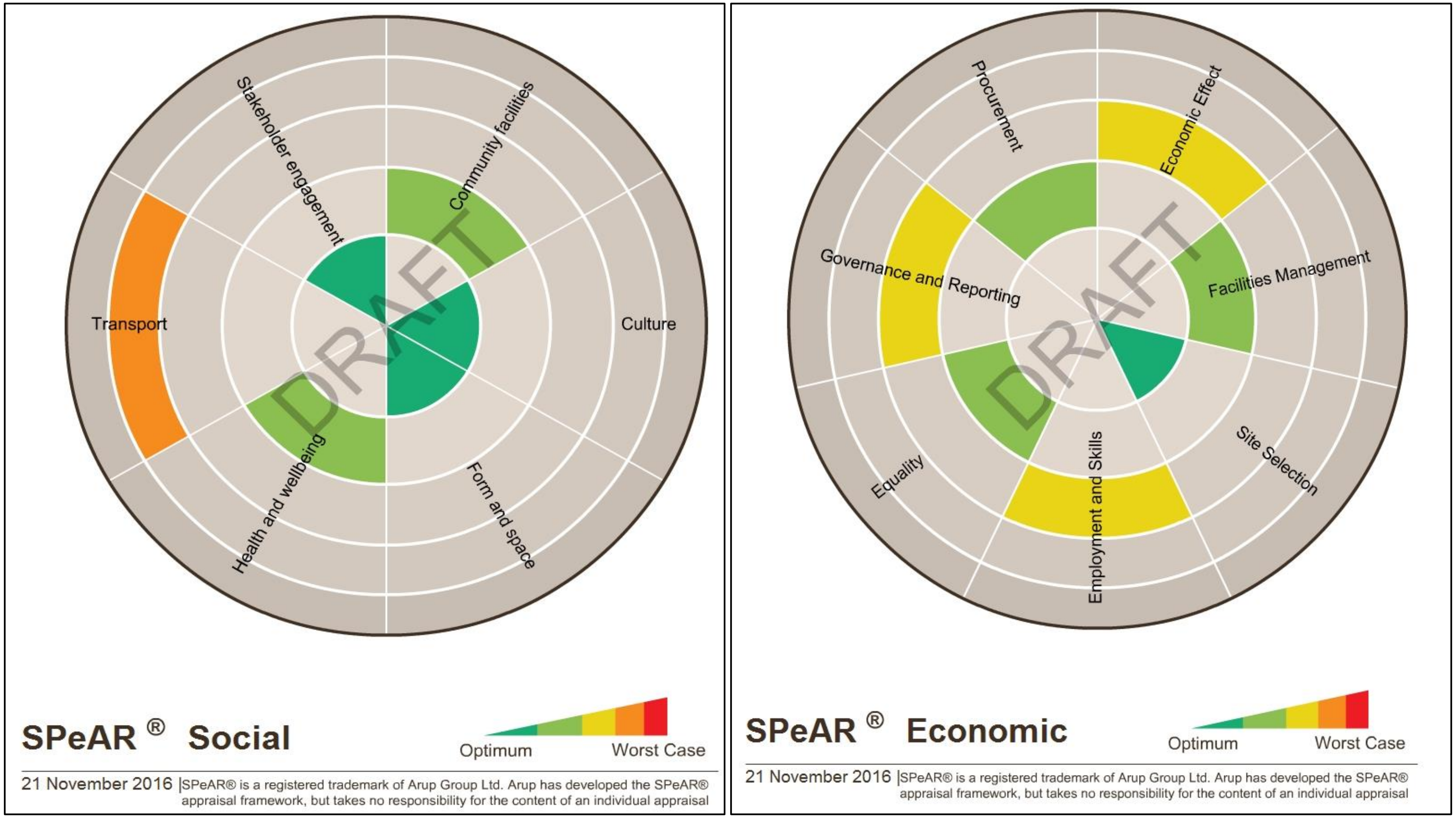
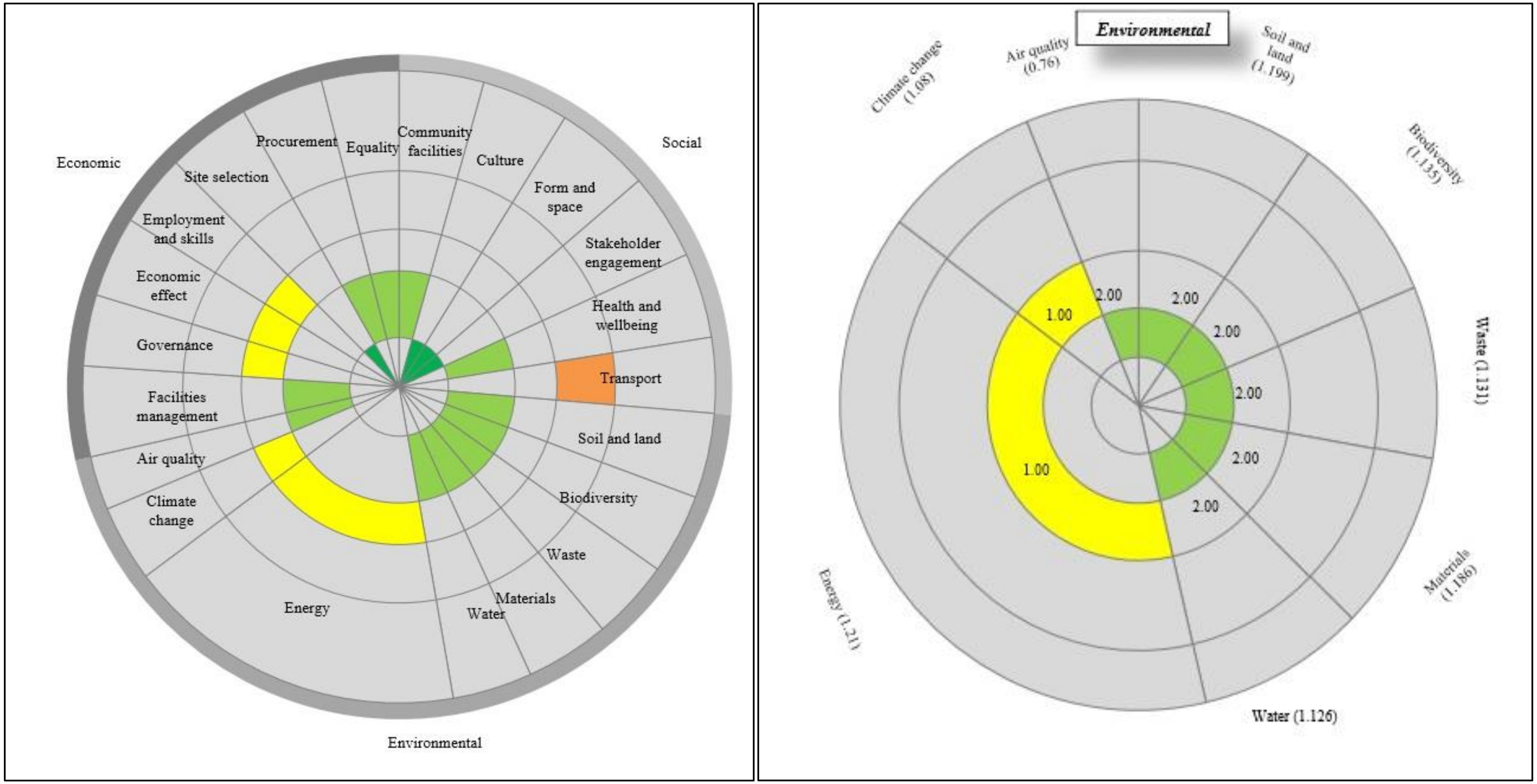
(a)



(b)

Figure 6.11:SPeAR® results for Aghdasiyeh Station, (a) overall score and environmental pillar (b) social and economic pillars

After reviewing the results from SPeAR®, the station was assessed using the USPeAR tool. The overall performance of the project as judged by the USPeAR assessment is presented in Figure 6.12. USPeAR shows the weighting of each indicator within each segment in the graph. For example, it can be seen that the indicator 'energy' is located in the yellow zone and it is deemed that transport has the highest importance and therefore the angle of the segment (and area of the pie) is proportionally larger than the other segments within the graph (Figure 6.12). In contrast, 'air quality' has the lowest weighting, and therefore, the angle of the segment is relatively much smaller. The values of the weighting used in shown at the outer edge of the graphs. 'Transport' and 'air quality', for instance have a weighting of 1.065 and 0.76 respectively.



Economic
Social
Environmental
Procurement
Equality
Community facilities
Culture
Form and space
Stakeholder engagement
Health and wellbeing
Transport
Soil and land
Biodiversity
Waste
Materials
Water
Energy
Climate change
Air quality
Facilities management
Governance
Economic effect
Employment and skills
Site selection
Environmental
Climate change (1.08)
Air quality (0.76)
Soil and land (1.199)
Biodiversity (1.135)
Waste (1.131)
Materials (1.186)
Water (1.126)
Energy (1.21)
2.00
2.00
2.00
2.00
2.00
2.00
1.00
1.00

(a)

(b)

Figure 6.12: USPeAR results for Aghdadasiyeh Station, (a) overall score and environmental pillar (b) social and economic pillars

6.3.2.1 Interpretation of the findings

This section will provide an interpretation of the findings of Aghdasiyeh Station demonstrated in previous section.

The issues associated with growth of population have been discussed in Chapter 2. With respect to Asian cities, Azami et al., (2015) state that "*Asian cities will double in size over the next 20 years, with more than 40 million people added each year*". The author adds that the 21st Century will be the century of urban development for Asia. However, there are challenges such as how to provide the basic amenities such as food, water, shelter, transportation, education and sanitation for its urban population, without disturbing the ecological balance (UN-Habitat, 2012). Having said that, moving towards sustainability is a fundamental concern, especially for Asian cities. This should be a long-term perspective whilst adopting appropriate strategies, which allows responding to human fundamental needs and ensure a better future (Russo and Comi, 2012).

Urban development planning and sustainability concerns were raised about four decades ago in Iran, though still most of the Iranian cities suffer from what might be termed unsustainability. In other words, many, if not all, of the cities in Iran face major challenges in terms of the environmental, social and economic dimensions of development (Barakpou and Keivani, 2015). The underlying results behind this is very different in each of the cities because of local context and conditions, however the overall goal in this project has been to remove the underlying causes of a poor transportation system, and promote infrastructures which are undoubtedly less unsustainable.

However, this lack of sustainability has caused serious issues over time. For instance, environmental challenges include high and ineffective energy consumption, destruction of natural environment, air pollution, water, soil, and other related problems. According to the World Bank (2005), the cost of environmental degradation in Iran, such as water, land and forest, waste, and CO_2 emissions, was projected to be about 8.8% of Iran's GDP (equivalent to US$10 billion) annually. About US$8.4 billion of this amount is due to damage to the country's national economy, and US$1.6 billion to the global environment through greenhouse gases (e.g. CO_2). This has led to the high use of natural land resources and hence a 50% reduction in the size of forests in the last 50 years. In addition, there is much degradation of water resources across the country both in quality and quantity (Barakpou and Keivani, 2015). Furthermore, International Energy Agency (2010) stated that the intensity of final energy consumption in Iran is approximately twice the world average. In general, different environmental indicators show increasing unsustainable development in recent decades in Iran (Barakpou and Keivani, 2015).

Thus, the question is that what are the obstacles to achieving sustainability in Iran, and how can we remove the underlying reasons for being unsustainable, to alternatively introduce more sustainably infrastructures (Azami et al., 2015). Underground stations have been constructed in Iran, without using any, yet essential, sustainability tool to assess and monitor. In which case USPeAR appears to be a useful tool to facilitate this, both through improvement and enhancement of sustainability.

Looking at USPeAR results (Figure 6.12), this section presents the analysis of the results considering the hierarchy of needs for sustainability improvement giving a clear example of virtuous cycles. It mainly describes the indicators with performance lower than the yellow zone (i.e. Score 1, 0 or -1). It gives an explanation of the indicators performance and also proposes solutions to improve their performance. The ideas for improvement have been taken from the benchmark, which was Farringdon Station.

Energy (Score 1, Weighting 1.21)

A major concern in Iran is energy. As has been stated above, Iran's energy efficiency is almost half of the global average. Looking at USPeAR results, the energy indicator has a score value of 1 and a high weighting, therefore this needs to be improved. By creating virtuous cycles within the graph, it can be said that energy can largely affect (or be affected by) aspects of transportation and economics. Furthermore, Rajabi and Behairy (2016) argue that energy is a major issue, and it lies within the economic and the environmental aspect of sustainability. The author states that many studies have shown the importance of integrating the energy management system in both transportation and construction sectors (Rajabi and Behairy, 2016). Therefore, it is essential to demonstrate a high level of energy efficiency in an economically prudent system (Rajabi and Behairy, 2016). One of the solutions would be the use of renewable energy within the station, which would be new to Iran. Another would be to use Sensors within the underground station to monitor the actual usage of energy. Additionally, other options for energy savings could be explored.

Climate change (Score 1, Weighting 1.08)

According to Emadodin et al., (2016) and Modarres et al., (2016), urban sprawl and the unsustainable land use has resulted in the variation of local climate in large cities in Iran.

However, for example for this purpose, looking at the benchmark (i.e Farringdon Station), as a part of Crossrail programme for the Farrigndons' station, there is CO_2 Commitment Scheme which considers the monitoring and reporting of CO_2 as well as hitting the targets and savings during the construction.

Although the city population is expected to increase, some mitigation and resolutions have been suggested by the author and discussed with the team at Farringdon's station to support growth whilst minimising the emissions and therefore less damage to our environment. One of the solutions is energy saving consideration which includes regenerative braking on trains which saves up to 25% of electricity used as it has been done by London Underground used at the Cloudesley Road substation on the Victoria line for a five-week trial (Transport for London, 2015). Having said these, it could be understood that CO_2 production and energy can greatly impact climate change. Hence, this indicator with the weighting of 1.08 is in high priority to be concerned about.

Transport (Score 0, Weighting 1.065)

Since the project itself is a transportation project, decisions to build it are posed as a solution to the current crowded surface as well as the extreme pollution in the city. The results of USPeAR implied that is in a substandard zone within the USPeAR diagram. By improving the transportation, air quality can be affected. It can be seen that air quality's weighting is not very high, and it is in the best-case zone, which would be beneficial to improve and ultimately to reach exemplary. This shows that improving either transportation or air quality indicators will result in a positive impact of both, as they are relevant. One suggestion for the station is using alternative methods for transporting materials rather than causing traffic on the surface and leading to the air pollution, as has been done at Farringdon Station.

Governance and reporting (Score 1, Weighting 1.003)

Barakpou and Keivani (2015) highlights that one underlying reason for the high levels of unsustainability in Iran is the lack of governance. Although the importance of governance has been understood, so far government and formal institutions are incapable of realising its practical application. This lack of knowledge has led to dramatic issues, such as the waste of resources (Barakpou and Keivani, 2015). Also, the author highlights that adequate measures in order to improve current urban governance, as an underlying solution for this existing issue and it will ultimately have advantages such as improvement in policy making and reducing the role of public institutions in discharging routine duties and services. This is needed at a state level before it can be manifested down to projects such as the station being considered.

Economic effect (Score 1, Weighting 1.147)

Another essential indicator to consider is the economic effect. This indicator has a high weighting of 1.147 and it has a poor performance. Indicators such as energy, transportation and material within the project can affect this indicator greatly. Energy management plans, for saving of energy, and transportation management plans, to improve overall economic situation of the community, are some mitigation measures as has been done for Farringdon Station. However, this indicator also considers the impact of the project on the surroundings' economic conditions. Improving this indicator could be beneficial by helping the economic aspects of community too. It could be argued that with the construction of this station and the metro as a whole the ability to move (e.g. to work) is improved which could improve the local economics – that said this very much is determined by the availability of jobs. Again, something that lies outside the direct remit of this station project.

Employment and skills (Score 1, Weighting 1.02)

Employment and skills has categorised into the yellow zone, emphasising the need for improvement. Knowing that Iran has recently faced threats on its employment and skills, improving this indicator will help to get the project moving in a more sustainable way. Similar to Farringdon's station, one suggestion would be to provide work opportunities for local people and to advertise the opportunity for all groups of people to be able to join. Providing training for the team and staff as well as conducting school lessons for students who are interested to join this field later is a pre-requisite for this to succeed.

Reviewing the indicators with low scores, and creating virtuous cycles, where possible, and essentially assessing their interrelationship could assist in identifying the most important indicators and understanding its interactions with others. This could be beneficial to the stakeholder/decision makers as they monitor a project at different stages, and it can give them different milestones and goals.

USPeAR can act as an enabler for decision-makers/stakeholders to have a clear view of the project performance and assess the indicators that are worth improving, based on their weightings and the virtuous cycles. The aim is to get to the ultimate goal of achieving excellent credentials in terms of sustainability, which is in the centre of the USPeAR graph. A major barrier for so doing is the economic aspect of a project where tight budgets restrict required investments. If the budget of the project is limited and there is no opportunity to improve a series of indicators, and in particular, all the essential ones, the question remains as to which indicator to improve – the one that has the highest weighting / importance and is the most cost effective. The following section will describe how the results of USPeAR can be combined with a cost-benefit analysis (CBA) to facilitate decision-making by prioritising indicator based on their effectiveness for improving overall sustainability of the project in a cost-effective way.

6.3.3 Applying CBA to Aghdasiyeh Station

The previous section discussed the primary assessment of Aghdasiyeh Station, which showed that most of the indicators do not perform to the exemplary or best practice. According to the proposed framework, the next stage involves utilising CBA for budget allocation purposes and to improve the overall performance of the project (i.e. to a more ideal situation closer to Farringdon Station performance).

This section explains the steps undertaken to conduct the CBA for Aghdasiyeh Station.

6.3.3.1 Costs and benefits components

As explained in the Chapter 3, to conduct CBA for Aghdasiyeh Station a 30-year evaluation period was considered, as the station was designed for this period. In order to undertake CBA, further meetings with staff at Aghdasiyeh Station were conducted and wherein indicators with poor performance were discussed. For Aghdasiyeh Station, six core indicators (previously discussed) have the poorest performance within the project. The associated costs and benefits are now considered within this section. Estimations of cost and the benefits of each alternative (i.e. indicator) have been gathered, with the help of staff at the station, as presented in Table 6.3. The table provides a series of recommendations for making further improvements to the station. According to the suggested recommendations, the associated costs and benefits are estimated and shown. .

It should be noted that the costs presented in Table 6.3 are the initial costs associated with making improvements, and will occur during the initial year of construction (i.e. I_0 in equation 3.3), however, benefits are considered for a longer term (i.e. 30 years perspective). Costs occurring during the 30-year evaluation period have also to be considered. These are operational costs which are associated with replacements, renewal, repairs and/or maintenance of physical parts and components. For example, LED lightings asset life is only three years and it, therefore, has to be replaced ten times within 30 years of design life of the station. The next section investigates the asset life of the alternatives proposed in detail.

Table 6.3 describes the considered benefits and their associated components. However, due to insufficient data for Aghdasiyeh Station, the benefits have been estimated for each indicator for the whole evaluation period (i.e. 30 years), and then it has assumed that this amount is equally distributed for each year.

Table 6.3: Cost-benefit analysis of Aghdasiyeh Station

Core indicators	Sub-indicators	Objectives	Alternatives	Cost (initial year)	Benefit (30 years)
Energy	• Energy supply • Energy conservation and efficiency • Energy monitoring • Day lighting • Heat demand • Cooling and ventilation	**To monitor and conserve energy** • Energy conservation • Energy monitoring • Day lighting	• Use alternative energy sources, such as solar panels • Monitor energy throughout the station using censors • Provide lights which use less energy and are therefore more cost effective	Energy savings activities have been investigated on both construction and office sites. Identified options are using solar panels and LED lighting, which leads to brighter and natural environment. LED lights are more efficient with less maintenance cost compared to the standard lighting. The overall cost is estimated to be £1,619,670.00.	The benefits can be summarised as reducing electricity and energy consumption and lowering the CO2 emission. Benefits is estimated to be £22,250,000.00
Climate change	• Carbon management plan • Social impact of climate change • Physical impacts of climate change • Economics of climate change	**To reduce the impact of climate change** • Carbon management plan • Social impact of climate change • Physical impact of climate change • Economics of climate change	• Review/conduct studies regarding the carbon management plan • Investigate the impact of climate change, such as high temperatures within the station • Investigate the cost of physical climate change such as flood-preparation • Review/conduct studies for cost of climate change (physical/social)	Studies need to be done in order to gain an understanding of the relevant costs of climate change and to establish the carbon footprint, to seek ways to reduce both, and to set a target to achieve this. This requires a team of staff including researchers and environmental specialists, provided with enough resources and facilities to prepare appropriate documents and this cost is estimated to be £1,029,500.00.	Mitigate events such as flood and heat waves, which can bring delays and increase costs, and affect the overall Tehran economy as well as the local people. Other economic costs associated with the disruption, which can be reduced, are the value of lost time suffered by train passengers and the repair costs to the rail infrastructure. The reduction can therefore improve overall passenger comfort. Such an extreme event could cause damages up to £1m which could be mitigated. This is estimated to be £16,100,000.00.

Transport	• Public transport infrastructure • Pedestrian design and facilities • Cycle design and facilities • Waterways • Freight traffic • Low emission vehicles • Private vehicle use • Air travel	**To improve transport aspects** • Cycle design and facilities • Low emission vehicles • Private vehicle use	• Designing park space for bikes • Use of low emission vehicles within the station	There is a possibility for bike parking to be located nearby the station. Also, the vehicles used underground could be upgraded to low emissions ones either for construction or maintenance and operation and it could be regularly checked. This is estimated to be achieved at a cost of £13,274,387.00.	Stations typically provide a range of facilities related to the rail journey; however, it could be improved by facilities which are directly relevant such as providing bike's parking space or encouraging use of low emission vehicle. The former will facilitate the opportunity for people travelling with bike and therefore more passengers and the latter prevents illnesses and complains arising from the issue. The overall benefit from low emission vehicles and more facilities is estimated to be £80,000,000.00.
Governance and reporting	• Monitoring and evaluation • Information disclosure and reporting • Strategy • Risk management • Donations to voluntary and community organisations	• Monitoring and evaluation strategy • Risk management	• Constant monitoring and evaluation of the project with respect to the ultimate goal • Developing a sustainability strategy • Having an accurate risk management plan	This requires a team to provide programme/project plan assessment, including measures of delivery at key milestones. The team should also assess whether the scheme is on track to deliver the anticipated benefits and details of any benefits realised. Identification of any changes to the scheme, for example, changes to design of the scheme and details of the reasons should be part of their duties. Having a team and providing facility to do research have been estimated to cost £527,000.00.	The ultimate benefit of monitoring and evaluation throughout a project would be reducing the financial risks associated with scheme elements and their mitigation during the construction period. Also the benefits from identifying factors in achieving cost forecasts and/or managing costs has to be considered. This is estimated to be £20,000,000.00.

Economic effect	• Value for money • Distortions to local economy • Vitality and regeneration • Carbon pricing	• Distortions to local economy	• Traffic and surface disruption due to construction/maintenance or negative impact of dropping the nearby housing cost	Improve the economy for example by reducing the average waiting time for the trains or average waiting time for purchasing tickets, alternatively the form of new pedestrian links, better way finding, improvements to transport interchanges and specific measures designed to increase accessibility for persons with restricted mobility. Other measures include providing better connections between a station and the surrounding area or quicker onward connections to other destinations. This is tied to the solution such as extra wagon for the train which in overall have been estimated at a cost of £4,715,000.00.	The benefit can include to encourage more frequent travel regardless of any changes to the train service and therefore facilitate economic growth and development opportunity. The estimated benefit could be £35,500,000.00.
Employment and skills	• Labour standards • Employment creation in construction • Employment creation in operation • Training • Access to finance • Social mobility	• Labour standards • Training	• Insurance for staff or identifying their right within the organisation • Adequate training for staff	To improve employment and skills, measures such as providing adequate training for the staff working in the station, providing health insurance and generally avoiding illness, injuries can be adopted. This would have a cost of £209,000.00.	This will lead to the ultimate benefits from saving regarding the injuries or claims due to the working environment conditions or accidents within the station. The benefits have been estimated to be £6,100,000.00.

(Details are given in Appendix E)

6.3.3.2 Asset life estimations

The asset life is considered as the minimum expected period for a structure or item to perform within its specified parameters. For conducting CBA, it is crucial to understand the asset life of each item, since the need to replace or repair an item will influence the long-term cost effectiveness of the whole system (Woods and Kellagher, 2004).

Within this section, initial costs of making improvements to each indicator have been estimated, which is considered to be the initial year of the construction, operational costs occur between years 1 to 31 of operation. This mainly depends on the asset life of each item, and how often it has to be replaced or repaired, which ultimately will give the cost of replacement and maintenance of each alternative during that period.

Asset life data was mainly collected via the literature. Table 6.4 presents asset life of energy category components that have been used in this research. However application of green and sustainable sources of energy are the non-physical components of this category, i.e. is a research based activity, and is considered to be valid for 30 years, based on the discussion with the team at Aghdasiyeh Station.

Table 6.4: Life expectancy of the alternatives (Energy category)

Proposed alternatives	Life Expectancy (years)	Reference
Energy supply		
Solar panels	15	AECB (2015)
LED lighting	3	AECB (2015)
Cables and accessories	15	AECB (2015)
Application of green and sustainable source of energy		
Research	30	Meeting with team at Aghdasiyeh Station
Energy monitoring system		
equipment	15	AECB (2015)
Cooling and ventilation		
Central heating systems	15	AECB (2015)
Air condition	15	AECB (2015)
Piping and accessories	15	AECB (2015)
Labour	1	Meeting with team at Aghdasiyeh Station

The other alternatives, namely climate change, transport, governance and reporting, economic effect and employment and skills, are not manifested in physical components, but are more in policy forms. One example is design and research on transport, which intends to make sure the designs are aligned with the population who are using the facility, and provide a sustainable solution if there is a need for an amendment to the current system. Another example is the carbon management plan, which depends on the station's policy as to how often it needs to be reviewed. Accordingly, the asset life of each component has been discussed with Aghdasiyeh Station team and ultimately the minimum life for each alternative has been given in Table 6.5.

Table 6.5: Life expectancy of alternatives

Alternative	Intervention	Years
Climate change	**Carbon management**	
	Research	6
	Required Tools and Machinery	30
	Social impact of climate change	
	Research	6
	Required Tools and Machinery for social impact of climate change research	30
	Labour	6
	Physical impact of climate change	
	Research	
	Labour	1
Transport	**Design**	
	Research / equipment	30
	Low emission vehicles	10
	Private vehicle use	10
	Labour	1
Governance and reporting	**Plan assessment**	1
	Risk management	1
Economic effect	**Research**	10
	Adding extra train coaches	30
	Adding extra public buses	10
	Overall public transport improvement (technology, design, equipment)	10
	Labour	1
Employment and skills	**Job training**	3
	Insurance for staff/ equipment	3
	Events for university and career fairs	1

6.3.3.3 NPV calculations

According to the explanations given in Chapter 3, Section 3.3.1.3 and Equation 3.3, in order to calculate NPV for Aghdasiyeh Station the followings were required:

1. Overall costs estimations for 30 years + cost of the initial year for making improvement

2. Overall benefits estimations for 30 years

3. Discount rate

Based on the data presented in the previous section, and by considering the asset life of each item and the periodic needed for replacement of each solution, the 30-year costs of each category have been calculated.

The overall benefit has been estimated for each category and, thereafter, it has been distributed equally for 30 years operation of the station. The discount rate was assumed the same as the inflation rate for this project.

Using Equations 3.1 and 3.2, the value of cost and benefits (cash flow) is calculated for each year, and it has been discounted to the present and the total NPV for cost and benefits have been given. The details for each alternatives' NPV calculation has been given in Appendix E. An example has been presented below.

Example: For transport alternative year 1 the only cost is the labour costs, and benefits have been estimated to be £2,666,666.67 per year. The calculations are presented in Table 6.6. Accordingly, each years' costs and benefits has been calculated up to Year 30, and ultimately the final sum of both for 30 years associated the NPV have been calculated using Equation 3.3 (Table 6.7 presents the final NPVs, whilst further details are given in Appendix E).

Table 6.6: Cost-benefit analysis of 'transport' alternative (year 1- discount rate 8%)

Year	Cost	labour			
1			Hour	Unit price	Total cost
			700	£55	£38,500
		PV (cost)= $\frac{1}{(1+r_t)^t}C_{it}=\frac{1}{(1+8\%)^1}$ £38,500=£35,648.15			
	Benefit	£2,666,666.67			
		PV (benefit)= $\frac{1}{(1+r_t)^t}B_{it}=\frac{1}{(1+*8\%)^1}$£2,666,666.67= £2,469,135.80			

Table 6.7: NPV calculations

Energy	£10,085,011.91
Climate change	£4,549,167.68
Transport	£10,341,022.97
Governance and reporting	£6,358,594.10
Economic effect	£6,837,448.37
Employment and skills	£1,204,707.40

At this stage, in order to apply the real impact and benefit of each indicator, the weightings (given in Table 6.8) have been applied using 6.1. The results can be seen in Figure 6.13.

Table 6.8: Weightings of the poor performance indiatoes of Aghdasiyeh Station

Indicator	Weighting
Climate change	1.08
Economic effect	1.147
Energy	1.21
Governance and reporting	1.003
Employment and skills	1.02
Transport	1.065

Equation 6.1

$$Weighted\ NPV_i = NPV\ \times W_i$$

In which i is the selected indicator which to be improved and w is the associated weight.

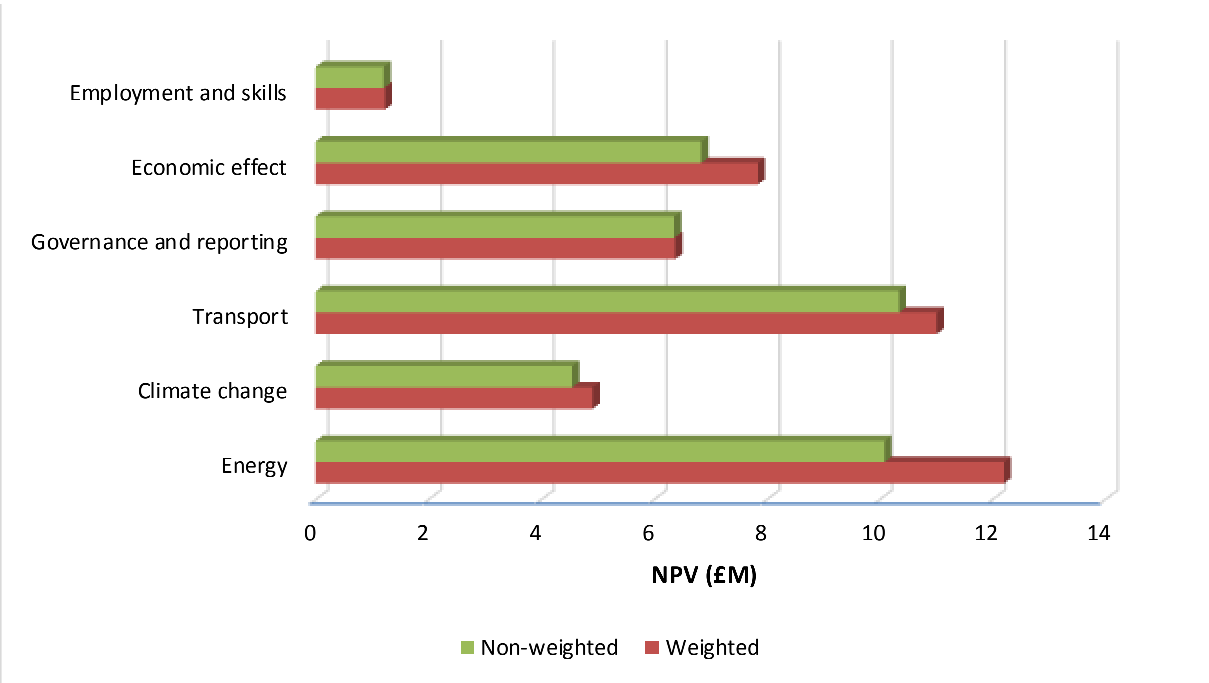


Figure 6.13: CBA results for Aghdasiyeh Station

Figure 6.13 presents the results of NPV with and without applied weighting. The weighted NPV results have changed since the weighting has been applied. This can be used to inform the decision-making process to give a clear overview of the future, and to identify which investment would be more beneficial. Considering the weighting of the indicators, the most beneficial indicator is revealed to be 'energy', this is followed by 'transport' and 'economic effect'. A comparison with the results of NPV prior to applying the weights, shows that the place of the top two indicators 'energy' and 'transport' has changed, but 'economic effect' remains unchanged in third place.

Energy indicator (W= 1.21), is the second top pre-weighted NPV, following transport with lower weight (W= 1.065) with a margin difference, i.e. just over £250k. This would make any decision to choose between them difficult. However, after applying the weighting, results became more suitable for judgment, by taking energy to first place, with a more significant difference between the two indicators. In contrast, when considering employment and skills (W= 1.02) and governance and reporting (W= 1.003), although the former has a higher weighting, CBA process has not changed their position. This is due to their low weighting and higher initial costs and lower potential benefits.

6.3.3.4 Sensitivity analysis for discount rate

The choice of discount rate can have a significant impact on the final NPV result, and so there should be a rational for selecting a particular value. Therefore, sensitivity analysis has been done to show the impact of a varying discount rate on this project. In order to conduct a sensitivity analysis, two additional discount rates, 7.3%; inflation for previous years and

12.6%; estimated inflation for the year 2018 (Trading Economics, 2017), were considered for the project. Figures 6.14 and 6.15 present the results of sensitivity analysis of varying discount rates for the NPVs of six alternatives of energy, climate change, transport, governance and reporting, economic and employment and skills.

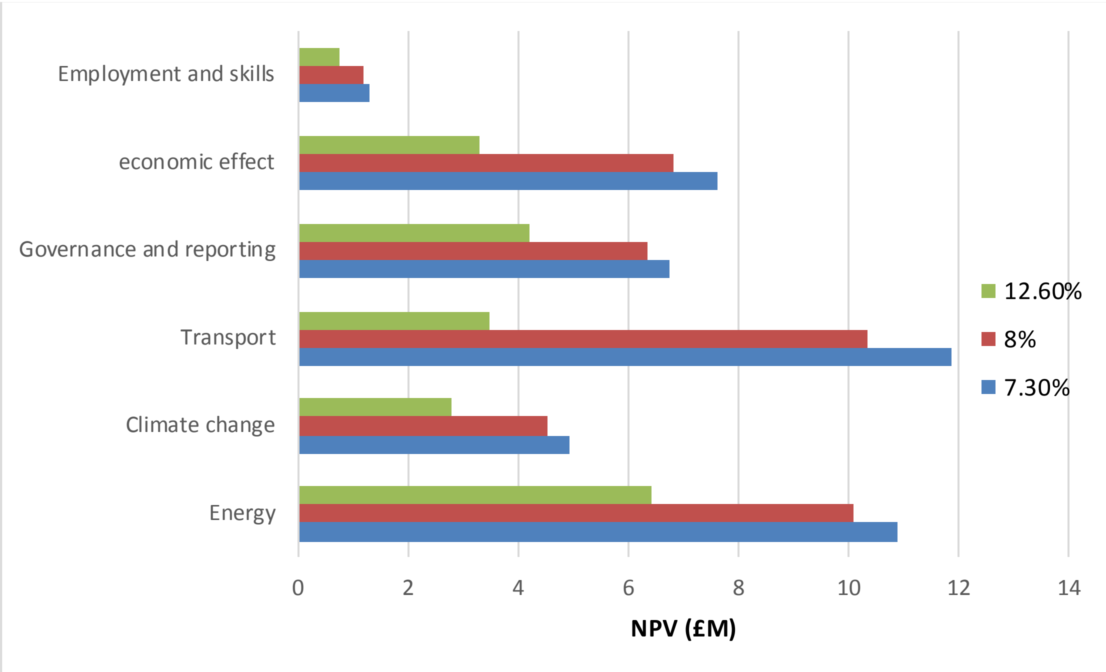


Figure 6.14: Sensitivity of NPVs to varying discount rate

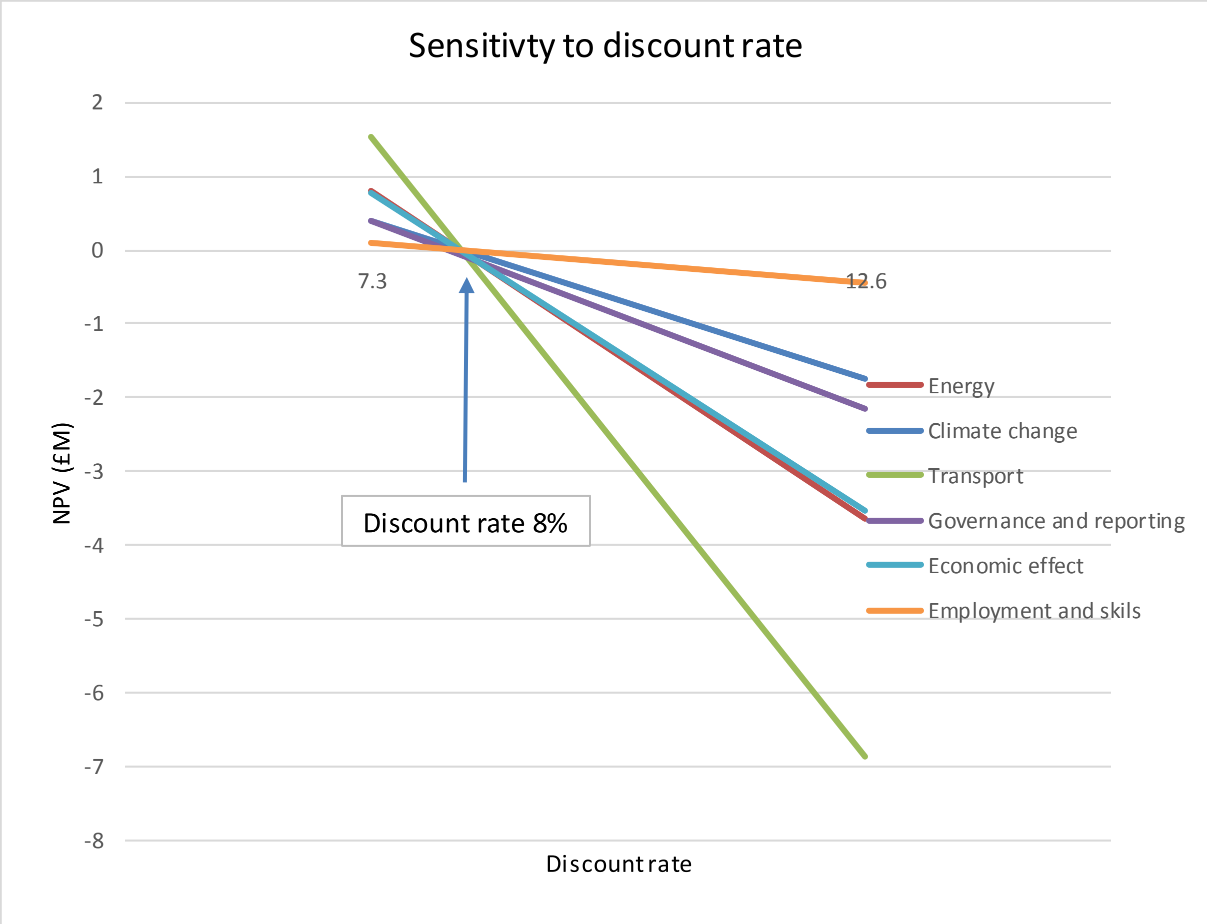
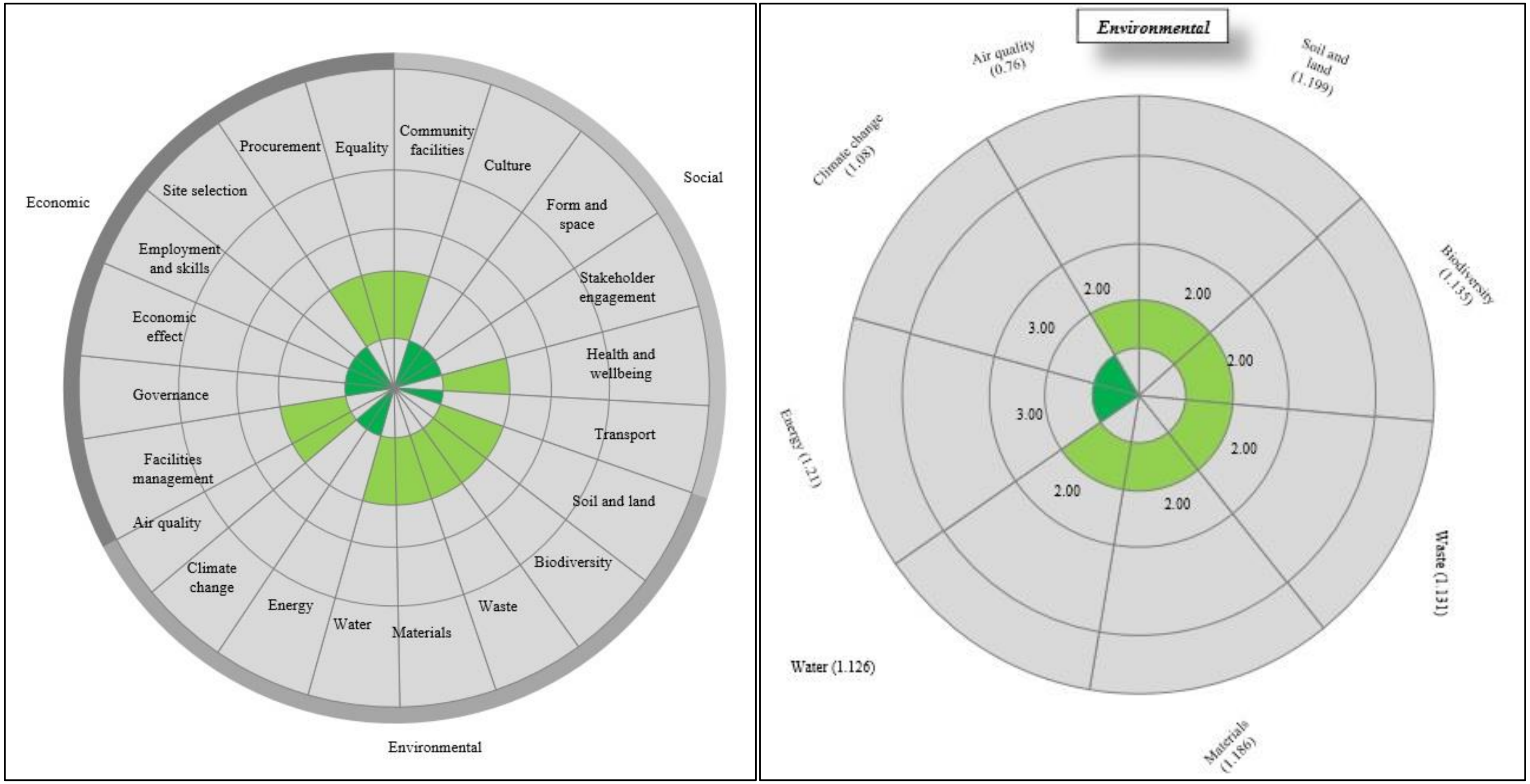


Figure 6.15: Sensitivity analysis for discount rate

As was expected from the theory, the results show a decay pattern relationship in cost effectiveness of six alternatives, where any increase in the discount rate resulted in a decrease of the NPV of all solutions. The most sensitive solution to discount rate is transport, whose NPV increases by over £8m (over 70%) for a 5.3% decrease in the discount rate (i.e. from 12.6% to 7.3%). The least sensitive alternatives, for the same change in discount rates, is the employment and skills, whose NPVs changes is less significant compared to other alternatives. Identifying the solution most sensitive to the discount rates can help decision makers, by showing the risks associated with that solution, as any change in discount rate (i.e. in this case inflation rate) will change the economic viability of the option significantly. As a mitigation measure, a policy maker might choose to select the less sensitive solutions, therefore, decrease the overall risk level of the project.

USPeAR, like SPeAR®, is a continuous process, which helps decision-making. Staffs at Aghdasiyeh Station have decided to take steps towards improving all the mentioned indicators according to their priorities and their available fund. By conducting the USPeAR assessment one more time and entering the new data regarding the improved indicators, it has been possible to show the improvements in graphical format. There are still indicators, which could be improved, but currently due to the limitation of the project, they are postponed to the future. The graphical result (Figure 6.12) shows the indicators that have performed very well initially, and some indicators to be improved were identified. However, as there is economic limitation within the projects and it is not possible to improve all at once. Only the indicators within zone yellow and orange have been improved. Figure 6.16 shows the current state of the project, after taking the improvement measures. However, this is a continuous process and it has to be done repeatedly to be closer to ideal goal of sustainability.


Economic
Social
Environmental
Procurement
Equality
Community facilities
Culture
Form and space
Stakeholder engagement
Health and wellbeing
Transport
Soil and land
Biodiversity
Waste
Materials
Water
Energy
Climate change
Air quality
Facilities management
Governance
Economic effect
Employment and skills
Site selection
Environmental
Air quality (0.76)
Soil and land (1.199)
Biodiversity (1.135)
Waste (1.131)
Materials (1.186)
Water (1.126)
Energy (1.21)
Climate change (1.08)
2.00
2.00
2.00
2.00
2.00
2.00
3.00
3.00

(a)

(b)

Figure 6.16: Improved USPeAR results for Aghdadasiyeh station, (a) overall score and environmental pillar (b) social and economic pillars

6.4 Summary

Chapters 4 and 5 have described the development of a sustainability assessment tool for UUS. This chapter has trialled the tool against two case studies (Farringdon Station in London- UK and Tehran metro in Tehran, Iran). The case studies demonstrated the inherent need for such an approach and highlighted the benefits that can be reaped in terms of informed decision-making. Each case study has been assessed using both SPeAR® and USPeAR tool. The assessment firstly scored each indicator from -1 to 3 (worst case to exemplary) along with providing narratives and supporting judgment for each indicator. The results of assessment using both tools, stating the performance of each project with respect to sustainability were presented. The final comparison between two tools has been made and the advantages of USPeAR have been discussed.

The first case study, Farringdon, was a great example of sustainable development; therefore, it has been used as demonstration of an ideal case, or benchmark, of underground exploitation. A second case study has been done and findings from Tehran Metro have demonstrated the tool's application, where a large number of indicators were identified that can be improved. Firstly, regarding the indicators that have a high weighting and did not perform appropriately, underlying causes and ways to improve and the role of weightings have been discussed. Secondly, in order to improve the poor performance indicators, the CBA method has been conducted. Furthermore, it has been demonstrated how CBA can be beneficial when coupled with USPeAR to provide a list of options for improvement according to their long-term sustainable benefits. The next chapter will discuss the research in more detail by critically re-viewing the findings and the development of the proposed framework.

CHAPTER 7: SUMMARY AND DISCUSSION

This chapter provides a critical review of how the research need was established, the research process adopted to meet this research need and the methodology adopted for the development of the UUS sustainability assessment tool, USPeAR.

7.1 Establishing the Research Need and Research Process

7.1.1 Literature review (Chapter 2 and 3)

The Literature Review established the high and growing importance of UUS (Section 2.2.2). It demonstrated that UUS development is a growing and evolving sector and that there is a body of evidence that suggests UUS will be extensively exploited for future use, and that there is an imperative for this to be done with sustainability in mind. There are currently tools that assess sustainability which cover an array of civil engineering projects, including underground aspects (as discussed in Chapter 2, Section 2.6) and each of these assessment tools are typically established by their own unique methods. The tools are reviewed in terms of two main categories: award-based tools and continual improvement tools, and there are also a number of tools designed specifically for UUS assessment, as discussed in Section 2.6.2, though none of them considers UUS in its entirety and importantly its impact on sustainability. Either they lack enough indicators to be fully representative of UUS application or they are limited to a single indicator set (e.g. for utilities) rather than a comprehensive sustainability tool. Sustainability was defined (in Section 2.5) and the relationship between UUS and sustainability was explored (in Section 2.5.1), which revealed the essential role of UUS in achieving a sustainable urban environment. To this end, UUS characteristics with respect to three pillars of sustainability, as well as UUS resources, were critically reviewed and discussed.

Having established the essential need, the literature review provides state-of-the-art classifications and descriptions of UUS, as well as a critical discussion of current commonly applied sustainability assessment tools (Section 2.6). Also includes the application of weightings, and application to UUS (Section 2.7). This overview of the literature exposed the fact that no individual UUS sustainability tool exists, hence the need to develop one. Based on the findings of this literature review, a methodology was proposed to develop a tool through reviewing existing tools and proposing modifications to the most appropriate one (Chapter 3), rather than creating a new tool. This review revealed SPeAR® as, potentially, the most suitable tool to be modified for application within UUS. The underlying reasons are:

1) SPeAR® provides a list of indicators specifically with respect to the three pillars of sustainability (i.e. this research is based on the three-pillar approach model, as discussed in Section 2.5)
2) There is flexibility within SPeAR®, which allows inclusion or modification of indicators
3) It is not award-based, and it is presented as a continual improvement tool, which could be applied to different stages of a project to show its strengths and weaknesses at different points of development.

7.1.2 Identifying the relevant indicators for UUS (Chapter 4)

Chapter 4 reviewed the application of the SPeAR® tool and justified its choice for modification. After reviewing the SPeAR® indicator system, a materiality review was conducted through a series of meetings. In this research, the author and Mr Peter Braithwaite worked as a team to conduct the materiality review and select the most appropriate indicators. Each indicator was studied thoroughly and its relevance to UUS investigated. In addition, a series of narratives and justifications as to why and how the indicators are relevant to UUS have been found. Some indicators irrelevant to UUS use were identified and justification for their removal made, and hence these indicators have been excluded. Finally, a set of indicators under three pillars of Sustainability – Environment, Society and Economy – have been considered relevant to UUS development.

7.1.3 Questionnaire (Chapter 5)

After selecting the relevant indicators to evaluate sustainable use of UUS, further improvement of the tool required weightings to be added to demonstrate the importance of each indicator. Expert opinion was elicited via questionnaires to gain information regarding the importance of each indicator, and from this, the final weighting was allocated for each indicator**.** Therefore, a questionnaire was developed and a group of experts were invited to participate in rating the importance of each indicator with respect to UUS. In total 25 experts (out of 100 contacted), who have relevant specialist skills, knowledge, and experience in civil engineering and sustainability agreed to participate to explore the importance of each indicator. These included those working in civil engineering companies, design engineering consultancies and academic institutions or those of notoriety in their field, including policy makers and government advisors. Accordingly, respondents with more than 10 years of experience in their field were selected (Chapter 5). The outcome of the questionnaire was the weighting for the final tool development.

7.1.4 Case study (Chapter 6)

To demonstrate the application of the USPeAR, Chapter 6 presented two case studies, one undertaken in Farringdon Station in London, UK and the other in Tehran metro station Iran. The former is well-known within the UK as an excellent project with respect to sustainability and has previously been awarded the CEEQUAL excellent award. The USPeAR assessment has been undertaken not only with the purpose of confirming the results of the CEEQUAL assessment, but also with the intention of using it as a UUS 'excellent' benchmark. The second case study was underperforming and USPeAR was used to highlight this and draw out areas for improvement. Each case study has been assessed against the USPeAR indicators and scores assigned through a series of meetings held with station staff at each location. Justification and narratives for the indicators have been provided and final scores have been assigned to each indicator. The final USPeAR (weighted) assessment results have been presented in graphical form and compared with SPeAR® (which is non-weighted), highlighting the benefits of the modified approach. Aghdasiyeh Station was revealed to be most capable of making significant sustainability improvements. Since cost is a concern in construction projects and funds are usually limited, application of the cost-benefit analysis method has been explored in order to demonstrate impact of cost (and benefits) on the project. This is a key addition within USPeAR.

7.2 Critical Review of the Research Methodology

7.2.1 Indicator selection

The method adopted for indicator selection is described in Section 3.2.1. It comprises a literature review as well as results from canvassing the opinions of sustainability specialists. It is worth mentioning that in the SPeAR® tool, in order to modify or exclude indicators, it is suggested to do a materiality review, which means making modification of indicators based on: risk; legal / regulatory / internal and external policy drivers; stakeholder concerns and societal trends; opportunity for innovation; and best practice/peer-based norms. To strengthen the choice of indicators, the literature was reviewed critically with to the intention of identifying the relevance of indicators presented by SPeAR® to UUS, hence more up-to-date evidence was included, providing narratives and justification of why the indicator is selected for and applicable to UUS.

A materiality review has been done by the author and Mr Peter Braithwaite in the form of a yes/no table. The process could be enhanced further through consultation with a team of experts to confirm the identified indicators, which could be done via a systematic process. The experts' engagement could be improved during the process by selecting more interactive methods, such as the Delphi method or structured "what-if" Technique (SWIFT) through a set of facilitated UUS workshops. A facilitated UUS workshop brings the opportunity for experts to discuss their opinions and to share their expertise of UUS, thus giving a higher possibility of identifying more UUS indicators, and therefore leading to a more robust UUS indicator set. However, due to the limited time and funding available for this research, this was not possible.

7.2.2 Expert judgements and limitations of questionnaire

To develop the questionnaire a 5-point Likert scale was selected as the most commonly adopted and appropriate method. Authors such as Hartley (2014) argue that 5 or 7 scale points are the most common form. However, the same author states that there are some researches using 2 points, or 4 points, hence disregarding the middle point and literally forcing the respondents to make a clear choice. On the other hand, there has been evidence to suggest that including or eliminating the middle point can lead to distortions in the results (Garland, 1991). A significant fact within the questionnaire is that for most of the indicators, the largest proportion of responses fall into the categories of neutral, good and very good, and only a few indicators have a high agreement on very poor or within the poor category. This goes back to the limitation of questionnaire design and also the fact that when respondents record their ratings on a Likert scale, there is a tendency to go for neutral or good points rather than any other (Hartley, 2013). Furthermore, limited number of respondents for the questionnaire had some effects on the final scores, due to not being able to capture extreme views. This issue has been previously raised in the other studies, such as Hartley (2013). More detail regarding this point is provided below.

The opinions of a group of experts were consulted via the questionnaire to develop the weighting system. For this purpose, the range of expertise was necessarily diverse, although all those consulted had high levels of experience. As for the number of experts from whom to obtain information for any study, it was deemed crucial to select a sample from the population to avoid bias, and to precisely reflect the research population as a whole (Ott and Longnecker, 2008). The literature review suggested a range of methods for selecting samples according to the requirements, however a number of related studies suggest a minimum of 20 samples may be satisfactory (Babuscia and Cheung, 2014; Tversky and Kahneman, 2014). The resource limitations of this study resulted in 100 experts being contacted, of which 25 actually took part in the research.

Having said that, there are issues associated with having this number, for example a lack of responses in some categories or having more responses from a specific group of people. These most commonly occurred least response from national policy makers and researcher, and client representative possibility due to the lack of knowledge or interest in the subject area namely UUS. On the other hand, there was a higher engagement of the academics and contractor, followed by consultants and construction material produces and manufacturer. The high engagement of the academics shows the interest in the subject of UUS, as it is nowadays promoted, and most countries are starting to benefit from this aspect of the ground. A drawback of having a high number of participants from this group is that their knowledge might be limited to the literature, with little actual field experience and, therefore, to not consider the practical aspects of UUS and sustainability. Having said that, there was high engagement from the construction material producer and manufacturer, which is a positive point as it brings the opportunity of having the viewpoint of practicality and field experiences. However, this unbalanced number of participants in different fields could lead to an underestimation or overestimation of the importance of some indicators.

Another limitation of this research is highlighted by the standard deviation process. There is no concept as a good or bad standard deviation, however, a larger standard deviation means that data is more spread which shows disagreement between respondents. However, it was not possible to highlight its full implementation through a small sample set of this research.

Within his research, some indicators had a high standard deviation due to the different groups of people giving different rankings. Involving a larger number of experts in the process could help to highlight the indicators which prompt disagreement, and finding out the underlying reasons.

Hence, it could be concluded that the developed weighting is based on the available expert panel, which was possible to arrange for the purpose of this research, and their expert judgement. It should be pointed out that the developed weighting is not definitive, yet it offered the opportunity to test the potential impact of such a panel, but there is room for improvement. For example, to address this as well as involving the whole group of respondents, an alternative approach could have been used for data gathering such as running focus groups or by applying the Delphi technique. In the former approach, all the experts are gathered together in one place for a series of brainstorming sessions. The latter method is a structured-process for collecting and condensing the knowledge from a panel of experts in two or more rounds (Quyên, 2013). However, these methods are time-consuming and expensive, as more than one round is required (Yu et al., 2015), and for this reason the panel was conducted as described.

7.2.3 Questionnaire analysis (weighting)

To analyse the results obtained from the questionnaire, the weighted average methodology was selected, whilst previously different methods such as Monte Carlo stimulation had been looked at. After running a Monte Carlo simulation, it became apparent that the results proved to be the same as the results from the weighted average methodology. The latter method is a much simpler method to analyse the responses from questionnaires. The weighted average methodology is the most common way to combine scores on criteria.

However, there are more complex and well-known methods such as: analytical hierarchy process (AHP) (Saaty, 1980), Fuzzy analysis and even combined AHP Fuzzy analysis. The AHP method is a way of solving multi-criteria decision-making problems, including the preferences. The AHP approach can be utilised to generate a group decision with only one round (Yu et al., 2015). Compared to other methods such as Fuzzy, it is less time-consuming and has lower costs (Yu et al., 2015; Allouche et al., 2000). Although AHP has not been used directly for questionnaire analysis due to the large number of indicators and comparisons required, however, in order to take advantage of such a widely-used approach, AHP has been used to verify the results from the questionnaire. Pairwise comparisons between core indicators has been done and a final weighting for each of the core indicators has been obtained. The results have been compared with the results of the questionnaire (Chapter 4).

7.2.4 Implications of the developed weighting

Within this research, the weighting system has been developed on a consensus basis, informed by local and international experts, which is known to be one of the most appropriate ways for developing comprehensive assessment categories and criteria (Grace 2008). Such a development is a complicated process in nature, but systematic involvement of experts assisted in overcoming the issue.

The developed weighting, utilised within a continual improvement tool, which gives a graphical presentation of the performance of the project with respect to the indicators, allows the users to monitor the weaknesses and strength of the project at its different stages, and compare the results within each phase. It is, therefore, possible for the stakeholders/users to set a goal or milestone and track their progress. A graphical representation of the tool, showing the applied weight by the width of each segment of the graph, the position of each indicator in relation to the others is immediately clear for the user. In other words, the developed weighting system in this manner allows the user to easily compare the weighting or importance of each indicator within each pillar. Furthermore, the way it is presented gives a representation of the importance of each indicator in a quantitative way in each phase of a project, which gives a clear and realistic evaluation of an indicator, and shows the criteria which are poor and require improvement.

Lastly, since the weighting has been designed on a consensus basis with local and global experts, it is seen to be applicable worldwide, as it does not include any specification regarding geology or economics of the country, along with location impacts.

Having said that, it is notable that there was a limited number of participants within the utilised process and, consequently, the results may vary with a larger group of people. It is essential to mention that the approach was taken to test the methodology and appropriateness of a developed sustainability tool for UUS, and it does not provide a definitive answer. Further recommendations on improvements to the tool have been given Section 8.3.

7.2.5 The developed tool

The procedure presented in Section 3.3 shows how a UUS tool can be used, and explains the steps that need to be undertaken by decision-makers to assess sustainability of UUS. The tool highlights the assessment results in a graphical presentation, which helps to demonstrate the strengths and weaknesses of the project together with the relevant weighting of the indicators, which is a representation of the highly important criteria to be considered (in a hierarchy) by decision makers. The developed tool shows great potential as a research tool, because it provides a database for selecting indicators of future UUS projects. It has the advantage of being able to be used at any time during the project and presents a clear understanding of a project's performance, irrespective of context, i.e. locally or globally. Additionally, as one of the major considerations during any project is cost, being coupled with cost-benefit analysis yields an ultimate result that is likely to be of direct use to, and therefore welcomed by, decision-makers. The tool can also be further developed to reflect a more complicated procedure of UUS assessment by allowing the trade-off between indicators. This will allow the tool to be adjusted to be more specific to the project, location and stakeholder's or decision-maker's needs. This will allow the tool's outputs to be more relevant to a range of different projects with completely different context and local conditions.

The following sections then discuss different aspects of the application of the tool, such as who can benefit from the use of the tool, and what decisions may need to be made that they have to be aware of.

7.2.5.1 USPeAR process

Figure 7.1 shows the procedure that needs to be taken to utilise the tool.

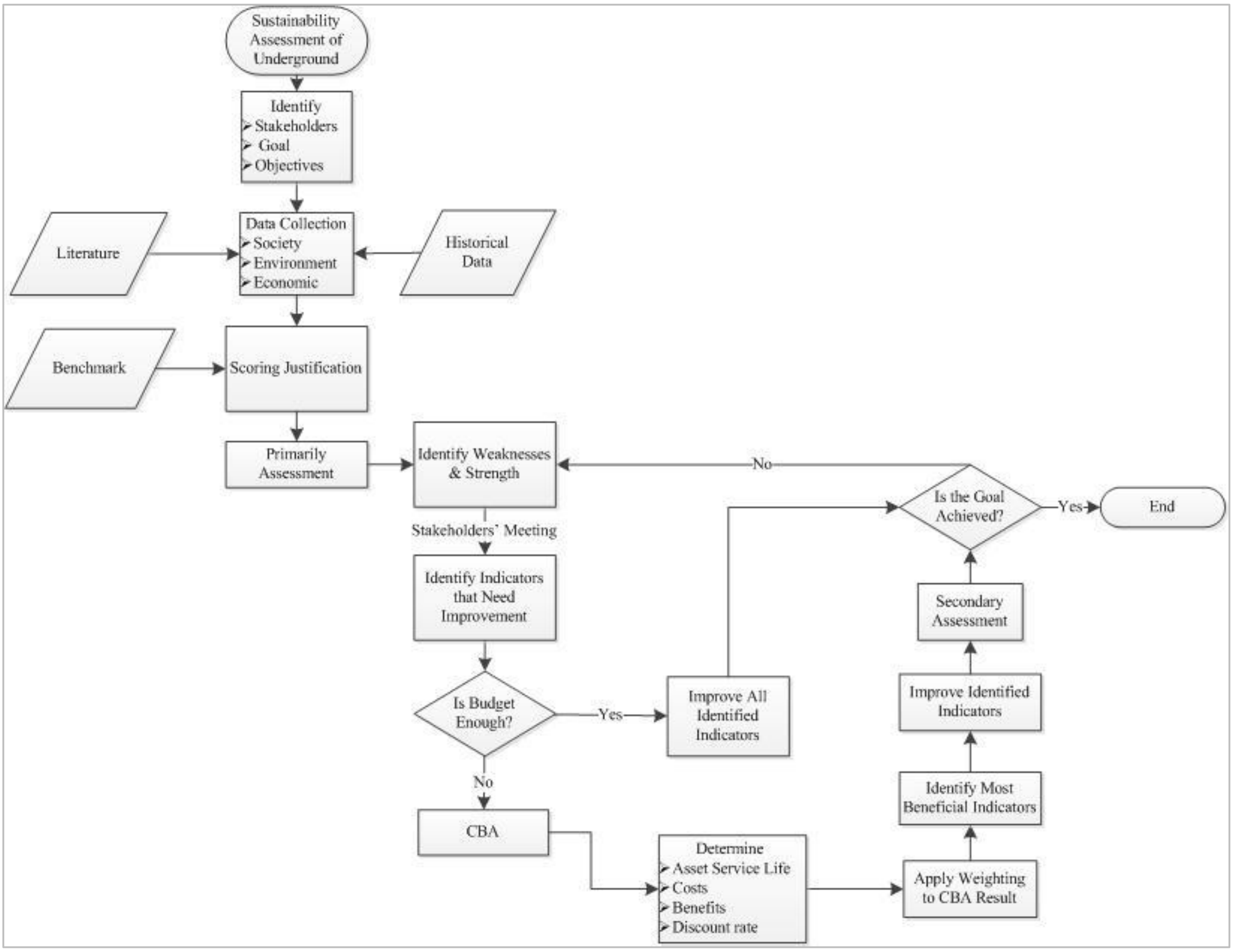


Figure 7.1: USPeAR Process

It is essential to note that the tool could be applied to different phases of a project. It could be used early in the project to identify the key indicators, or used during the design stage to compare the implications of different designs and guide decision-making. It also can be used when a project is completed or during the operation stage. However, it is the stakeholders' choice to decide at which stage of the project, and how often, the tool is intended to be used.

7.2.5.2 Key decisions for applying the tool

The following measures are recommended when applying the tool:

- Identify stakeholders, project goals and objectives

It is necessary for users to identify the project stakeholders, and to discuss the aims and objectives of the project at the beginning. This will help to set milestones and to encourage stakeholders to collaborate in discussing the main purpose of the project; identify the location, stage(s) of the project at which the assessment should be used; and/or other considerations, such as who would be affected by the project or who would benefit from it. This will help stakeholders to have an overview of their projects and its milestones. Using this tool will then help to avoid further disputes, for example, between stakeholders, and enable users to identify how far their objectives have been achieved each time they run the assessment, and to what extent the ultimate goal of the project has been achieved.

- Data collection and scoring justification

Another fundamental step is the data collection process. The data, where possible, should be referred to project documentation or validated by third party sources. It should also be gathered from different sources: literature, review meetings or site visits, and consultation with key stakeholders. Collected data should be checked and verified to make sure that the data collection was methodologically and statistically sound. Then it is required to put a score justification into the tools. Another project that has the same purpose with excellent performance can also be used as a benchmark when coming up with a final scoring.

- Cost analysis

When the poor indicators are identified, a range of solutions can be proposed to make improvements to the project. A similar project that has previously been rated with an excellent performance can be used as a benchmark, and ideas can be drawn out of this benchmark for implementation in the current project. Overall, an accurate cost-benefit analysis is essential, in terms of all costs and benefits within the lifecycle of the project, with an appropriate discount rate.

7.2.5.3 Potential end-users

The tool has been designed to be applicable worldwide. The following is a list of potential beneficiaries:

- Local authorities and policy makers, who would benefit from more efficient sustainable use of underground space, either financially or environmentally.

- City and County Councils and other sustainability agencies, who have a role in managing the UUS and the ultimate impacts on the environment. Use of the tool will help them to deliver more effective solutions to, for example, transport infrastructure.

- Policy makers, regulators and non-governmental bodies, who are interested in, or affected by, the use of UUS. The use of the tool will help to get an insight into the various ways of bringing about more effective and sustainable underground practices.

- Tunnel engineering consultant companies, who are responsible for providing the design for tunnelling projects. This tool will provide a way to test their design in advance, and to determine the impacts of their proposed design on the environment.

7.2.5.4 Tool's transferability

Designing a tool to be applicable worldwide has been achieved through developing indicators and weighting that are independent of the geographical location or economic situation of a country. The indicator's review process, through materiality, was generally undertaken on a worldwide basis. For instance, if there was an indicator with best practice anywhere in the world, the indicator was included. Furthermore, during the utilised questionnaire, participants were asked to consider a general case of underground use, in order to be able to develop a weighting system for any possible facility going underground. Also the participants represented a number of countries and were asked to consider the indicators for worldwide application. Hence, the tool is transferrable to anywhere else around the world.

This was demonstrated through the presented case studies; Farringdon Station in London, UK, and Aghdasiyeh Station in Tehran, Iran, despite differences in sustainability drivers in these two countries, the tool was proved to help evaluate the performance of the projects, and to promote sustainability.

7.2.5.5 Impacts of including weightings on decision-making process

Within the field of construction, and specifically when sustainability is at stake, we find a vast and complex set of issues that need to be considered, including social, environmental and economic, which make it difficult to consider all relevant aspects of a project. As a result, simplified methods are needed in order to deal with the complexity of the analysis. In other words, there is a requirement for methods that aid in the interpretation of complicated information, in order for any decision to successfully contribute to completion of the project. Weighting can be the key when dealing with major organisational or business decisions which comprise a series of decision attributes and multiple decision alternatives. This is particularly important when dealing with sustainability assessment which, as discussed previously, has weighting at its heart.

Throughout the decision-making process, the goal is to find the most suitable from a set of alternatives. In these situations, weighting can help to evaluate different options and provide a demonstration of its real-life impact. Moreover, it is challenging to assess the extent of uncertainty of these results. Therefore, an intelligent decision-making is required, which includes full consideration and knowledge of the assessment method, and weighting has been considered as the most effective way to achieve this.

Within this research, the case study demonstrated the difference between a weighted (USPeAR) and unweighted form of SPeAR®. The weighted graph enabled users to identify the indicators with high importance, which make a difference to the project. It gives a hierarchy of importance and makes it clearer which indicator is more beneficial and worth improving, and how it can help to improve the overall sustainability of the project.

Alternatively, and to take this to another level, within this research weights have been combined with cost-benefit analysis, which has shown the impact of weightings when cost is the main concern. The inclusion of weighting, along with cost considerations, has changed the results of the evaluation, and has shown the priority of the indictors with budget concerns and real-world considerations.

7.2.6 Case studies

Two case studies have been selected for this research to show the application of the tool, namely Farringdon Station in the UK, and Aghdasiyeh Station in Tehran. Farringdon Station was previously rated as 'excellent' performance using CEEQUAL tool, as reported in the literature. However, Aghdasiyeh Station in Tehran was thought to rate as poor performance, as there was not much sustainability governance in Iran. Hence, the final goal was to use Farringdon Station as a benchmark for Aghdasiyeh Station, firstly, to aid the process of scoring within Aghdasiyeh Station, and secondly, to help to draw ideas from their excellent performance to improve Aghdasiyeh Station's performance.

Results obtained by USPeAR for the Farringdon Station project confirmed the previous findings of the CEEQUAL assessment, as results show that all indicators fall into the exemplary area (the comparison of two will be used further for verification of USPeAR in Section 7.3). The case study proved the tool's efficacy in both delivering an assessment and in providing additional understanding as to why it achieved this outcome; some of the factors behind the success of the project have been discussed and have been considered for improving Aghdasiyeh Station.

The second case study results show that there are many areas of the project capable of being improved. Furthermore, as the case study was used in two different countries having very different contexts to test the proposed theoretical framework, it is evident that the tool can be used globally, and the results could be used to faithfully represent the decision-makers' goal.

Regarding the experts who were consulted when undertaking the case study assessments, the main person who was consulted was head of the sustainability management team. The assessment has been done using their knowledge and their judgment. However, the results might be affected by their bias through overjudging an indicator or including their personal interest. An alternative and more precise approach could be involving or undertaking the assessment by consulting the local planning authority, since it is local planning authority's responsibilities to ensure that the sustainability appraisal has been carried according to the related planning and legislations.

7.2.6.1 CBA

The two case studies have been assessed using both USPeAR and SPeAR®. The comparison between both tools' application has been explained. USPeAR presents the performance of each project and gives a hierarchy of needs, identifying indicators to be improved. However, there is a need to find a sustainable way to improve all identified indicators or to prioritise them for improvement. It has been shown that weightings give this to some degree, but still choices depend very much on the specific context of the project. Therefore, this research suggests combining the results of an USPeAR assessment with CBA in order to achieve best results, especially within budget constraints. The case of Farringdon Station proved to be an excellent project with only two indicators needing to be improved, in this case there was less requirement for CBA.

However, with respect to the Tehran metro station, the result of the USPeAR assessment showed that 6 core indicators out of 21 core indicators needed to be improved. The challenge was to decide which ones are the more important ones to be improved, with the limited budget, and how to do so. Therefore, CBA was used to prioritise the options for making improvements based on the costs and benefits implied by each indicator. CBA allowed for consideration of the initial costs and long-term, yet uncertain, benefits of each alternative. Within CBA there was the opportunity for identifying and categorising costs and benefits, whilst considering NPV, which means deciding about the period for the analysis and how the costs and benefits will change over time. This process includes applying a discounting rate to the future cash flows. Within this research, inflation rate was assumed as the discount rate, and the sensitivity of results to the choice of discount rate was tested by using three different values. The overall results of CBA show that it could be successfully coupled with USPeAR tools, and was able to facilitate the process of assessment of the Aghdasiyeh Station. However, the results were sensitive to the discount rate, which shows the high importance of the choice of discount rate and the impact of inflation. This will be discussed in more detail in the following section, along with other advantages and disadvantages.

7.2.6.2 Pros and cons of including CBA

Due to the uncertainty arising from costs and benefits estimations and the concerns about future, some research studies judge CBA as incapable of being used in complex investment decisions (Asplund and Eliasson, 2016). However other authors such as Jones et al., (2014) underline that CBA is one of the most comprehensive tools for decision-making. Further discussions on the advantages and disadvantages of including CBA within the process are provided below.

- Accuracy of data

One of the most important factors within the CBA analysis is data collection; a low accuracy is largely related to the amount of information available about the project, specifically if the tool is applied in the initial stages of the project. As well as this, the validity of CBA is linked to the comprehensive consideration of cost-benefit categories. This certifies the reliability of the measurements and indicates how consistent and inclusive the measurements are.

As explained in methodology section, the calculation of cost is a straightforward process, for instance, the costs of pipes or new energy-efficient equipment, which ultimately reduces the use of fossil fuels and greenhouse gas emissions. However, a cost-benefit analysis calls for monetary values for these benefits, whereas the benefits are usually in non-monetary terms in a sustainability concept, for example in terms of environmental preservation, which is an important aspect of UUS. Allied to this, are some indirect advantages specific to underground construction, which are challenging to identify, for example, how a community can benefit from a new station and, therefore, it is usually ignored in calculations. This has been the case for this research too, as due to the time limitations of a doctoral research project, it was not possible to identify all the costs or to include all indirect advantages.

- Discount rate

Apart from uncertainty with costs and benefits estimations, the next consideration is the choice of discount rate. The choice of discount rate plays an important role. If there is even a minor disagreement over costs and benefits of an option the choice of discount rate may result in divergence between acceptance and rejection of an alternative. Hence, a careful consideration has to be given to the choice of discount rate. Within this research, discount rate was considered equal to inflation rate. According to Trading Economics (2017), Iran's inflation was 8% in 2015/2016. However, a sensitivity analysis was undertaken and the analysis was carried out with respect to two different discount rates of 7.3% and 12.6%, the results show sensitivity to the discount rate, where applying a higher discount rate decreases the NPV. Whilst there may be some uncertainty on selecting a discount rate, studies have shown that potential losses due to uncertainty in this area are small, compared with the potential gains of utilising CBA technique as a selection criterion (Asplund and Elliasson, 2016).

However CBA is a popular method when long-term planning is considered, some of its advantages are listed as below:

- It allows identification of all possible alternatives for intervention;
- It assesses the costs and benefits associated with different alternatives systematically, for example, based on a common unit of measurement (money);
- It identifies costs and benefits linked with each alternative, including social and environment aspects, meaning that both direct and indirect benefits can be considered;
- Costs and benefits are measured, including the degree of uncertainty in the available data);
- The costs and benefits of a project over its life span are considered, meaning that future costs and benefits are included in the NPV;
- Inclusion of a fixed criteria or objective in order to reach a decision, namely NPV;

7.2.7 Implications of adopting the proposed system on decision-making

During the lifecycle of a facility (i.e. design, operation and maintenance), the argument is over benefit. The existing sustainability assessment tools are effective instruments to deliver more sustainability solutions within the construction industry, as well as promoting a revolution in the areas of design, construction, operation and maintenance. As a result, different industries within the construction field have commonly used them to report the social, environmental and economic performance. Different assessment methods have become less efficient over the years in coping with the growth of populations, therefore, ultimate demands are made on the practitioner to develop new assessment tools, or improve the existing ones. Although the rating system, and consequently the weighting system, exist in the literature, authors such as Poveda and Young (2015) argue there is a need for flexibility within the system, to allow its implementation for a wider range of projects and to improve the evaluation of sustainability performance. By incorporating a continuous performance improvement element, USPeAR allows projects and organisations to base their final sustainability performance score on actual performance and weights of implemented strategies (i.e., indicators) while allowing improvement throughout the years.

- Performance, reduction of impacts and meeting sustainability objectives

USPeAR is a tool developed for the implementation of performance excellence tactics throughout the lifecycle of a facility. As goals and objectives are established in early stages of the projects, the weighting designed for evaluating the performance of each criteria becomes an essential element for the effective assessment of goals and objectives at organisational and project levels.

From the evaluating and improving performance viewpoint, the tool provides continuous support by enabling the user to make an assessment as many times as required, or when it is essential to input lessons learned or updated data for the organisation and managers to confirm, modify or eliminate existing processes.

The implementation of a sustainability weighting system indicates adherence to a specific vision for sustainability, whilst addressing the needs of the organisation or project's stakeholders. Each criterion included in the structure of the weighting system is meant to assist the decision-making process throughout the project lifecycle. The USPeAR tools target excellent project performance, according to the available budget for project owners, through the implementation of more efficient processes. Therefore, the adoption of CBA aids the process to find the most beneficial indicators which have to be met in order for projects to reach the target level of sustainability.

7.3 Tool validation

This section explains the process that has been used to verify the stages involved for the development of the tool, including verifying the results of assessment with CEEQUAL assessment from the literature.

7.3.1 Weighting development

To develop the weighting, a panel of experts has been used. The panel has been selected from professionals in the industry, who are well experienced in construction.

In order to validate the results of the questionnaire, it has been compared with the literature review. This process started by comparing the first part of questionnaire with the literature review and sustainability concept. Since there was only a limited number of respondents within the expert panel, the result from the part of questionnaire was not used, as it was not possible to confirm their reliability.

In order to validate the second part of the questionnaire, the results were compared with AHP process, which was based on the authors' and Mr Peter Braithwaites' judgement, and the literature. The results of the two methods were compared and the justification or the differences were highlighted.

7.3.2 USPeAR verification using CEEQUAL

The developed tool was tested during two case study sites. Farringdon Station was already assessed by CEEQUAL, which demonstrated CEEQUAL Excellent (90.3%). Assessing Farringdon Station with USPeAR was expected to yield similar results.

According to CEEQUAL, the Farringdon station has been performed excellently with respect to the following categories: heritage and town planning requirements, noise and nuisance, piling into the aquifer, designing out waste, community relations and engagement, energy and carbon, material use and sustainable procurement, and ecological habitat creation.
Similarly, within USPeAR, the same indicators have been considered. Heritage and town planning requirements are considered within 'archaeology and local heritage', under the 'culture' indicator within social category. Noise and nuisance, which considers the impact of the works, has been the potential nuisance to the surrounding environment within USPeAR,

and has been considered in 'distortions to local economy' under the 'economic effect' indicator, and within the economic pillar. Piling into the aquifer, which within Farringdon station goes back to protecting the aquifer from potential contamination to the satisfaction of the Environment Agency, meaning that soil and soil contamination has to be considered, is linked to the 'soil and land' indicator within the 'environment' category. Designing out waste within CEEQUAL is closely linked to the indicator 'waste' within the 'environment' pillar, which covers all types of considerations with respect to waste, including designing out waste. Another aspect of Farringdon within CEEQUAL was 'community relations and engagement', which includes the project team collaboration and engagement, which has been similarly covered within 'stakeholder engagement' in the 'social' pillar.

Energy and carbon is another major concept of Farringdon station in CEEQUAL assessment, which has been covered in USPeAR as well. The USPeAR indicators 'energy demand' and 'climate change' include issues linked to energy and impact of carbon on the project within the 'environment' pillar.

Material use and sustainable procurement is another consideration in CEEQUAL and has been performed excellently in Farringdon Station, which is the same case in USPeAR. Procurement has been covered in the 'procurement' indicator within the 'economic' pillar. It focused on material use and the aim of the material use plan had been to assess the performance of potential materials in order to influence the design and specification.

Ecological habitat, which investigates the impact of the project on habitat, the same indicator, has been included in USPeAR under 'biodiversity' in environment pillar.

All indicators contributing to the excellent rewards of CEEQUAL were also included in USPeAR. The USPeAR results confirmed the CEEQUAL findings. However, the comparison shows that CEEQUAL is a general tool applicable for all infrastructure projects, whilst USPeAR not only considers the indicators included in CEEQUAL, but also includes a range of indicators applicable to UUS. Hence the comparison demonstrates that USPeAR could be used as a comprehensive tool for underground projects.

7.4 Summary of the Discussion

This chapter has critically reviewed the research methodology adopted in the development of a sustainability assessment tool for UUS to determine the impact of an UUS project on sustainability. The chapter has also discussed the implications of the tool with the attached weighting and its potential benefits for users and highlighted the steps needs to be consider during its utilisation. In particular, the effectiveness of the tool and assumptions made throughout the research were discussed and, where appropriate, suggestions have been offered to facilitate future developmental work and improvements to the framework of the UUS tool.
Conclusions from the research, together with recommendation for further research, are presented in the following chapter.

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

The aim of the thesis came about principally as a response to the need to satisfy the knowledge gap identified through a critical review of the literature. This showed that whilst many sustainability assessment tools exist, none of them holistically account for urban underground space (UUS) i.e. specifically the impact UUS construction can have on sustainability of our environment both now and in the future. The research has demonstrated the vital need for development of a UUS sustainability assessment tool, which facilitates the opportunity for decision-makers to enhance urban sustainability. This gap provided the overarching aim of the research study, which was

> *to advise underground stakeholders through development and testing of a sustainability assessment tool consisting of an indicator system, with weightings attached where appropriate, that can be used to evaluate the contribution of underground space usage towards sustainability using a three-pillar approach.*

The tool would thus aid in determining the impacts of sub-surface construction on today's urban development, whilst measuring its long-term sustainability.

With this in mind the thesis presented herein has sought to provide an improve understanding of how UUS and its use can contribute towards achieving a sustainable urban environment. Moreover, it has provided a tool (USPeAR) that can measure and compare the performance of UUS projects through the development of a series of weighted indicators.

USPeAR helps to monitor a project from the earliest design stages, and provides a clear understanding of the project performance throughout the different phases (design to end use). The proposed excel-based tool provides an assessment strategy with a series of indicators and weightings which can help decision makers to assess sustainability. The tool consists of an indicator scoring system supported via narratives and project-specific justifications. Running the tool gives clear presentation of the performance of the project including its strengths weaknesses and virtuous cycles. In addition, it can be combined with CBA to yield more realistic long-term performance results that consider the costs and benefits of respective UUS indicators. The effectiveness of the tool was demonstrated using two case studies: one in the UK and another one in Iran.

8.1 Accomplished Work and Main Findings

The research has met the objectives outlined in Chapter 1 by:

- ✓ Conducting a comprehensive critical literature review on the potential uses of underground spaces in urban areas, specifically in terms of functional infrastructures, passing and living spaces and critical infrastructures.
- ✓ Reviewing the current state-of-the-art knowledge of existing sustainability assessment tools/indicator systems explicitly, in terms of award-based tools and continual improvement tools, as well as a series of tools/indicator systems specifically designed for UUS.
- ✓ Introducing a series of indicators designed specifically for underground space use, based on SPeAR® assessment tool and materiality review introduced by this tool.

- ✓ Designing a questionnaire methodology and using it to obtain a weighting system for the selected indicators

- ✓ Applying the indicators and developed weightings to two case study sites and, based on the findings, identifying the advantages and disadvantages of its application

- ✓ Presenting a tool with a sustainability assessment strategy to assess underground space utilisation (i.e. combining the tool with CBA analysis) and therefore developing a methodology, applicable worldwide, to address the question of what sustainability impact can an underground structure have or how an UUS project can be improved

It is possible to draw the following conclusions from the research:

- Chapter 2 fulfils Objectives 1 and 2 of the thesis. The critical review of the current state-of-the-art, as presented in Chapter 2, introduces current underground space development in urban areas and the interrelationship with sustainability. The world is increasingly an urban environment, and urban sustainability has become a core focus of attention in the global debate and one of the major concerns of modern societies. Therefore, underground space, as one of the most important urban resources, is of great significance to improve land use efficiency and to decrease the high traffic density of central urban areas. As well as this, the research demonstrated that extensive use of UUS highlights that underground spaces will be the future frontier for urbanisation due to surface land scarcity and environmental considerations. Furthermore, Chapter 2 points to the fact that at present there is a knowledge gap with regard to sustainability assessment and the role of UUS; and a sustainability assessment tool, which helps decision-makers to enhance and improve sustainability, was yet to be devised. Chapter 2 also introduces an overview of existing sustainability assessment methodologies.

- Chapter 4 fulfils Objective 3 of the research in selecting the SPeAR® tool as the most appropriate tool to be further modified for USPeAR tool development. The SPeAR® tool has been reviewed and this identified the need for expert input to construct a set of indicators and narratives specific to UUS. SPeAR® was deemed to be appropriate because it does not include bias and provides a list of generic indicators that allow for modification / adjustment to be made based on different project needs and goals. A materiality review as well as a literature search has been carried out. The materiality review, as suggested by SPeAR®, formed a comprehensive assessment as it considers the relevancy of each indicator against relevant criteria. The resulting USPeAR tool consists of 88 indicators for UUS distributed under three pillars of sustainability.
- Chapter 5 fulfils Objective 4 of the thesis. Canvassing expert opinion was shown to be a viable means of determining the weighting of each UUS indicator. Structured questionnaires were found to be a useful means of eliciting expert opinion (see Section 3.2.2.1). Also, the standard deviation method was utilised to analyse the degree to which the participants involved were in agreement or disagreement on the importance of the indicators. This enabled the interest - or lack of interest - of some groups of participants on some indicators to be highlighted. However, this mainly reflected the limitations of the questionnaire, and highlighted that some higher standard deviations were only achieved because of the low number of respondents, hence the method would be more representative with a larger number of participants.

  In Chapter 5, a weighted average methodology was found to be an appropriate technique for questionnaire analysis with a weighted average method used to apply final weightings. As discussed in Chapter 7, the results obtained when using expert opinion will ultimately depend upon the range and quality of the experts considered (and this should be both diverse and high respectively).

- Chapter 6 fulfils Objectives 5 and 6 of the thesis. Therein two case studies have been used and USPeAR applied: Farringdon Station, in London, UK, and Aghdasiyeh Station in Tehran, Iran. Chapter 6 demonstrated that the proposed methodology could be successfully applied in completely different contexts and local conditions – a precursor for a generic UUS tool.
    - For the UK, USPeAR showed that the Farringdon Station project's performance was in fact exemplary; this was in accordance with a previous evaluation undertaken through CEEQUAL.
    - In Iran USPeAR showed that there were many places where the sustainability of the project could be improved. The USPeAR assessment allowed for a clear overview of the project's needs to be highlighted. More importantly, through the applied weighting system, a hierarchy of the most critical elements that could enhance sustainability was shown.
    - The final step of undertaking a cost-benefit analysis in combination with the result of USPeAR allowed these sustainability benefits to be considered alongside budget limitations. This allowed the decision-makers to allocate money based on a more informed basis.
    - The results of the USPeAR and CBA assessment within the applied case study (i.e. Aghdasiyeh Station in Iran) identified the poor indicators that could be improved and would yield the most positive NPV. A sensitivity analysis showed that they are sensitive to selected discount rate. However, despite the

disadvantages and sensitivity, CBA was revealed to be one of the most common methods for economic assessment and it has been successfully coupled with the developed tool within this research.

- A flow chart for the application of the tool has been provided. However, to deliver the most effective solution, it has been concluded that stakeholders, goals and objectives have to be identified in the early stages to avoid conflict in later stages of the project. Also, data collection has to be accurate and verified as fully as possible.
- The weightings in the manner adopted and presented have been shown to be an ideal way of developing a novel tool for UUS assessment. Not only is it based on the views of 25 experts who are well experienced, it has also been set to be globally applicable. It also benefits from being presented in the width of the segment of the graph, which simplifies the comparison of the weightings of indicators within each pillar.
- The tool is useful for everyone involved in construction and sustainability, who benefit from sustainability considerations alongside financial aspects, or individuals who are involved in policy making and are interested in the outcomes of developing more sustainable solutions.
- The developed tool demonstrates the impacts on decision-making by enabling the user to monitor and track the process against the set milestones and goals. There is an opportunity to update data or make modification and rerun the assessment, and also to repeat the assessment as required.

- The tool validation and verification, conducted through tool development stages, and the comparison with CEEQUAL results show that USPeAR could be used successfully on UUS projects.

8.2 Lessons Learnt from this Research and Additional Applications for the Framework

The work carried out and reported in this thesis mainly concerns the widespread ever-increasing development of UUS. As a part of this process, it is crucially important for those involved in planning, designing and constructing in cities to evaluate the principles of sustainable construction with respect to its use. Within USPeAR all sustainability issues do not have to be dealt with at once by the project team upon completion; the benefit is that sustainability targets and actions can and should be prioritised during the whole life of the project. This is a more extensive way of dealing with sustainability that facilitates the chance to distinguish virtuous cycles, delivering numerous advantages and benefits to the stakeholders. As well as this, the USPeAR *'process'* makes sure relevant sustainability indicators of UUS are given within the tool, and assessment is undertaken against these in order that the *'outcome'* is more sustainable use of UUS. The process means that as designs develop, the project can be tracked against UUS indicators and help monitor what is improving or, just as important, what is getting worse. This strategy makes sure that project teams go far beyond sustainability rhetoric, box ticking or chasing points, and instead consider a much broader range of issues, such as *'risk, equality and employment concerns*'.

There should be an underlying philosophy with the project team to have regular milestones along the project timeline with a view to constantly monitor the project as it progresses. The baseline data gathered in the USPeAR assessment tool delivers an evidence-base for potential sustainability issues / opportunities across the project (before they occur) and directly informs the way in which the project is likely to (or can) contribute to sustainable development.

8.3 Recommendations for Further Research

With regard to Sections 8.1-8.2, it can be concluded that the aim and objectives of this present research work, as specified in Chapter 1, have been addressed with development of the USPeAR tool. Nevertheless, these assertions have been based upon a number of assumptions and simplifications. Notwithstanding these limitations, the applications of USPeAR have demonstrated the promise of the tool, which can be successfully utilised to assess the impact of UUS on sustainability of our environment. Even so, to further develop and improve the convenience of the tool to stakeholders and decision-makers, the following further research is recommended. The limitations that have thus far been identified can only be resolved through further research, to sharpen up and enhance the proposed USPeAR. These are presented below:

- The research presented in this thesis mainly relies on the information obtained from a review of current literature or existing expert knowledge. Further research is therefore recommended to provide the opportunity to extend the knowledge where possible, for example identifying historical data and finding new indicators with respect to desired areas of UUS, as the information can be used to determine the impact, and probability of a relevant indicator having this impact, according to the historical data.

- The research could be further enhanced by applying the developed tool to numbers of different case studies and utilising feedback from new users to modify the indicators and their associated weight. This would provide opportunity to refine the tool by using more real-world examples and having feedback from users with different backgrounds and needs. This would potentially lead to a more comprehensive and user-friendly tool.

- The use of a trade-off between indicators can be investigated, which could be incorporated into the tool for the stage of scoring and ranking the indicators. This process could be used to allow all sorts of projects to benefit from this tool, even if their sustainability goals are totally different, and identify where some indicators are not applicable at all. As well as this, a trade-off between indicators should allow the division of weightings between indicators, which again needs a more in-depth study involving much larger stakeholder groups.

- Further research should also explore actual quotations and cost estimations for alternative planning / design of projects and to be considered within the tool. If there are different scenarios for the project, and stakeholders are unsure about it, a cost estimation of sustainability assessment will give an overview of how to implement the design of a project.

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APPENDIX A: MATERIALITY REVIEW OF INDICATORS

Table A.1: Materiality review of indicators

	Core Indicators	Original Indicator	Materiality Review						
			Risk			Legal/Regulatory/Internal & External Policy Drivers	Stakeholder	Innovation	Best Practice
			Financial	Social	Environmental				
Social	Community facilities	Recreation	*	*	-	*	*	*	*
		Education	*	*	-	-	*	*	*
		Healthcare	*	*	-	-	*	*	*
		Retail	*	*	-	-	*	*	*
	Culture	Respecting socio-cultural identity	-	-	-	-	*	*	-
		Cultural and religious facilities	*	*		-	*	*	*
		Use of environment	*		*	*	*	*	*
		Intergenerational and gender practices	-	-	-	-	-	-	-
		Archaeology and local heritage	*	-	*	*	*	*	*
		Art	-	*	-	*	*	*	*
	Form and space	Density, Height, scale and massing	*	-	*	*	*	*	*
		Public, private and communal space	*	*	*	*	*	*	*

		Landscape, townscape and visual impact	-	-	-	-	-	-	-
		Security	*	*	-	*	*	*	*
		Connectivity	*	*	-	*	*	*	*
		Microclimatic	-	-	-	-	-	-	-
	Stakeholder engagement	Identification and analysis	*	-	*	*	*	*	*
		Engagement process and feedback	*	-	*	*	*	*	*
		Integrating stakeholders comments	*	-	*	*	*	*	*
	Health and wellbeing	Access to green space	*	*	-	*	*	*	*
		Community cohesion	-	*	-	-	*	*	*
		Institutions and social networks	*	*	-	-	*	*	*
		Indoor environment	*	*	-	*	*	*	*
		Social vibrancy	*	*	-	-	*	*	*
	Transport	Public transport infrastructure	*	*	*	*	*	*	*
		Pedestrian design and facilities	*	*	-	-	*	*	*
		Cycle design and facilities	*	*	-	-	*	*	*

		Waterways	*	-	*	*	*	*	*
		Freight traffic	*	-	*	*	*	*	*
		Low emission vehicles	*	-	*	*	*	*	*
		Private vehicle use	*	-	*	-	-	*	-
		Air travel	*	*	-	-	*	*	*
Environment	**Soil and land**	Contaminated land	*	-	*	*	*	*	*
		Soil quality	*	-	*	*	*	*	*
		Drain age systems	*	-	*	*	*	*	*
	Biodiversity	Protected species and habitats	*	-	*	*	*	*	*
		Conserving and improving local biodiversity	*	-	*	*	*	*	*
		Habitat connectivity	*		*	-	-	-	-
	Waste	Construction waste management plan	*		*	*	*	*	*
		Waste in operation	*	*	*	*	*	*	*
		Hazardous/special waste	*	*	*	*	*	*	*
		Composting	*		*	-	*	-	-
		Designing out waste	-	-	*	*	*	*	*
	Materials	Materials efficiency in design	*	-	*	*	*	*	*

		Use of recycled or materials	*	-	*	*	*	*	*
		Environmental and sustainability impacts of materials	*	*	*	*	*	*	*
		Healthy materials	*	*	*	*	*	*	*
	Water	Water pollution	*	*	*	*	*	*	*
		Water resources	*	*	*	*	*	*	*
		Wastewater treatment and disposal	*	*	*	*	*	*	*
		Water monitoring	*	-	*	*	*	*	*
		Water supply	*	-	*	*	*	*	*
		Construction	*	-	*	*	*	*	*
	Energy	Energy supply	*	-	*	*	*	*	*
		Energy conservation and efficiency	*	-	*	*	*	*	*
		Energy monitoring	*		*	*	*	*	*
		Day lighting	*	*	*	*	*	*	*
	Climate change	Carbon management plan	*	*	*	*	*	*	*
		Social impact of climate change	*	*	-	*	*	*	*
		Physical impacts of	*	*	*	*	*	*	*

		climate change							
		Carbon sequestration	*	-	*		*		
		Economics of climate change	*	-	*	*	*	*	*
	Air quality	Ambient air quality	*	*	*	*	*	*	*
		Direct emissions	*	*	*	*	*	*	*
		Indirect emissions	*	*	*	*	*	*	*
		Ozone depleters	-	-	-	-	-	-	-
Economic	**Facilities management**	Usability	*	-	-	*	*	*	*
		Appropriate technologies	*	-	-	*	*	*	*
		Whole-life flexibility	*	-	-	*	*	*	*
		Operation and maintenance	*	*	-	*	*	*	*
	Governance and reporting	Monitoring and evaluation	*	-	-	*	*	*	*
		Information disclosure and reporting	*	-	-	*	*	*	*
		Strategy	*	-	*	*	*	*	*
		Risk management	*	*	*	*	*	*	*
		Donations to voluntary and community organisations	*	*	-	*	*	*	*
	Economic effect	Value for money	*	-	*	*	*	*	*
		Distortions to local	*	*	*	*	*	*	*

		economy								
		Vitality and regeneration	*	*	*	*	*	*	*
		Carbon pricing	*	-	*	*	*	*	*
	Employment and skills	Labour standards	*	*	-	*	*	*	*
		Training	*	*	-	*	*	*	*
		Access to finance	*	-	-	*	*	*	*
		Training	*	-	-	*	*	*	*
		Employment creation in construction	*	*	-	*	*	*	*
		Employment creation in operation	*	*	*	*	*	*	*
		Social mobility	*	*	-	*	*	*	*
	Site selection	Site location	*	*	*	*	*	*	*
		Planning intent	*	*	*	*	*	*	*
		Diversity/mixed use	*	-	*	*	*	*	*
	Procurement	Local sourcing	*	-	-	*	*	*	*
		Global sourcing	*	-	-	*	*	*	*
		Procurement strategy	*	-	-	*	*	*	*
	Equality	Affordability	*	*	-	*	*	*	*
		Designing for equality	*	*	-	*	*	*	*
		Impacts and benefits	*	*	*	*	*	*	*
		Land tenure	*	-	-	*	*	*	*
		Displacement	*	*	-	*	*	*	*

Signed by: Peter Braithwaite Signed by: Roya Zargarian

Date: 30/2/2016

*Materiality review of included indicators (Applicability is shown with *)*

APPENDIX B: QUESTIONNAIRE SAMPLE

This research survey is conducted as part of PhD research project undertaken at University of Birmingham. The aim of this research is to assess the contribution that underground space can make towards sustainable development. All responses you provide for this study will remain confidential. Your participation is voluntary and you may withdraw from this research any time you wish (only if you provide name or email address).

The new library of Birmingham has been chosen as a case study for this research.The library, one of the largest in Europe, is one of the most significant cultural projects to have been undertaken in the UK over the past decades. This major transformational project will contribute to the social, economic and environmental regeneration of the city for generations to come.

The library is located in the city's Centenary Square. It is comprised of a stack of four rectangular volumes, which are staggered to create various canopies and terraces.
Finally a spacious lower ground floor, which is extended up to the edge of the train tunnel, reaches out into Centenary Square. Lighting of this floor is supported through stepping terraces which enter the interior space. An amphitheater in the square is another source of daylight penetration. This floor is allocated to children along with the music library.

A series of generic indicators with respect to underground space use have been developed. You are asked to fill a short questionnaire, approximately 15 minutes , and rate the importance of each indicator with respect to the lower ground floor of the library *or any other project which has a similar use of underground space* .
There is an opportunity to leave a comment if you find an indicator irrelevant.

If you have any question about the questionnaire or the wider project please email me or give me a call.
Thank you very much for your time.

Roya Zargarian

Part 1) General question

* 1. Please tick the box to confirm that you have read and understand the information sheet for the above study and understand that your participation is voluntary and you are able to withdraw at any time and confirm that you understand any information will be kept confidentially in paper/electronic record.

◯ Confirm

2. Participant Information

Name

Email

3. Please choose your role within the organisation

☐ (1) Environmental activists

☐ (2)Construction professionals- Client representative

☐ (3)Construction professionals- Contratcor

☐ (4)Construction professionals- Consultant

☐ (5)Construction material producer & manufacturer

☐ (6)Local authority and policy makers and planners

☐ (7)Academics and researchers- Graduate

☐ (8)Government policy makers and researchers

* 4. Please confirm you have more than 10 years experience in your field of expertise

◯ Yes

◯ No

Part 2)

* 5. Please rate the importance of the three main pillars of sustainability in relation to the use of underground space (Spend 100 points between all)

Environment	
Society	
Economic	

* 6. Social Pillar – With the urban underground space facility in mind, please rate the impact of each indicator on sustainability (Please leave a comment if you find any indicator inappropriate)

	Very poor	Poor	Neutral	Good	Very good
Community facilities / Recreation	○	○	○	○	○
Community facilities / Education	○	○	○	○	○
Community facilities / Healthcare	○	○	○	○	○
Community facilities / Retail	○	○	○	○	○
Culture / Cultural and religious facilities	○	○	○	○	○
Culture / Use of environment	○	○	○	○	○
Culture / Archeology and local heritage	○	○	○	○	○
Culture / Art	○	○	○	○	○
Form and space / Density ,Depth,scale and massing	○	○	○	○	○
Form and space /Public,private and communal space	○	○	○	○	○
Form and space /Security	○	○	○	○	○
Form and space / Connectivity	○	○	○	○	○
Stakeholder engagement / Identification and analysis	○	○	○	○	○
Stakeholder engagement / Engagement process and feedback	○	○	○	○	○
Stakeholder engagement / Integrating stakeholders comments	○	○	○	○	○

	Very poor	Poor	Neutral	Good	Very good
Health and wellbeing/ Access to green space	◯	◯	◯	◯	◯
Health and wellbeing/ Community cohesion	◯	◯	◯	◯	◯
Health and wellbeing/ Institutions and social networks	◯	◯	◯	◯	◯
Health and wellbeing / Indoor environment	◯	◯	◯	◯	◯
Health and wellbeing / Social vibrancy	◯	◯	◯	◯	◯
Transport / Public transport infrastructure	◯	◯	◯	◯	◯
Transport / Pedestrian design and facilities	◯	◯	◯	◯	◯
Transport / Cycle design and facilities	◯	◯	◯	◯	◯
Transport / Waterways	◯	◯	◯	◯	◯
Transport / Freight traffic	◯	◯	◯	◯	◯
Transport / Private vehicle use	◯	◯	◯	◯	◯
Transport / Low emission vehicles	◯	◯	◯	◯	◯
Transport / Air travel	◯	◯	◯	◯	◯

Comments

* 7. Environmental Pillar – With an urban underground space facility in mind, please rate the impact of each indicator on sustainability (Please leave a comment if you find any indicator inappropriate)

	Very poor	Poor	Neutral	Good	Very good
Soil and land / Contaminated land	○	○	○	○	○
Soil and land / Soil quality	○	○	○	○	○
Soil and land / Drainage systems	○	○	○	○	○
Biodiversity / Protected species and habitats	○	○	○	○	○
Biodiversity / Conserving and improving local biodiversity	○	○	○	○	○
Waste / Construction waste management	○	○	○	○	○
Waste / Waste in operation	○	○	○	○	○
Waste / Hazardous/special waste	○	○	○	○	○
Waste / Designing out waste	○	○	○	○	○
Materials / Materials efficiency in design	○	○	○	○	○
Materials / Use of recycled or reused materials	○	○	○	○	○
Materials / Environmental and sustainability impact of materials	○	○	○	○	○

	Very poor	Poor	Neutral	Good	Very good
Materials / Healthy materials					
Water / Water pollution					
Water / Water resources					
Water / Waste water treatment and disposal					
Water / Water monitoring					
Water / Water supply					
Water / Construction					
Energy / Energy supply					
Energy / Energy conservation and efficiency					
Energy / Energy monitoring					
Energy / daylighting					
Climate change / Carbon management plan					
Climate change / Social impact of climate change					
Climate change / Physical impact of climate change					
Climate change / Economics of climate change					
Air quality/Ambient air quality					
Air quality/Direct emissions					
Air quality/ Indirect emissions					

* 8. Economic Pillar – with an urban underground space facility in mind, please rate the impact of each indicator on sustainability (Please leave a comment if you find any indicator inappropriate)

	Very poor	Poor	Neutral	Good	Very good
Facilities management / Usability	◯	◯	◯	◯	◯
Facilities management / Appropriate technologies	◯	◯	◯	◯	◯
Facilities management / Whole-life flexibility	◯	◯	◯	◯	◯
Facilities management / Operation and maintenance	◯	◯	◯	◯	◯
Governance / Monitoring and evaluation	◯	◯	◯	◯	◯
Governance / Information disclosure and reporting	◯	◯	◯	◯	◯
Governance / Strategy	◯	◯	◯	◯	◯
Governance / Risk management	◯	◯	◯	◯	◯
Governance / Donations to voluntary and community organisations	◯	◯	◯	◯	◯
Economic effect / Value for money	◯	◯	◯	◯	◯

	Very poor	Poor	Neutral	Good	Very good
Economic effect / Distortions to local economy	○	○	○	○	○
Economic effect / Vitality and regeneration	○	○	○	○	○
Economic effect / Carbon pricing	○	○	○	○	○
Employment and skills / Labour standards	○	○	○	○	○
Employment and skills / Training	○	○	○	○	○
Employment and skills / Access to finance	○	○	○	○	○
Employment and skills / Eemployment creation in construction	○	○	○	○	○
Employment and skills / Employment creation in operation	○	○	○	○	○
Employment and skills / Social mobility	○	○	○	○	○
Site selection / Site location	○	○	○	○	○
Site selection / Planning intent	○	○	○	○	○
Site selection / Diversity and mixed use	○	○	○	○	○
Procurement / Local sourcing	○	○	○	○	○

	Very poor	Poor	Neutral	Good	Very good
Procurement / Global sourcing	○	○	○	○	○
Procurement / Procurement strategy	○	○	○	○	○
Equality / Affordability	○	○	○	○	○
Equality / Designing for equality	○	○	○	○	○
Equality / Impacts and benefits	○	○	○	○	○
Equality / lend tenure	○	○	○	○	○
Equality / Displacement	○	○	○	○	○

Thank you for you time.

APPENDIX C: AHP RESULTS

Table C.1(a):Social pillar reciprocal matrix

Indicators	Community facilities	Culture	Form and space	Stakeholder engagement	Health & wellbeing	Transport
Community facilities	1	2.0	0.5	1.0	0.3	0.1
Culture	0.5	1.0	0.5	1.0	0.1	0.1
Form and space	2.0	2.0	1.0	1.0	0.2	0.1
Stakeholder engagement	1.0	1.0	1.0	1.0	0.5	0.1
Health & wellbeing	3.0	7.0	5.0	2.0	0.2	0.1
Transport	7.0	7.0	7.0	7.0	7.0	1.0
Sum	14.5	20.0	15.0	13.0	8.3	1.7

Table C.1(b): Normalized relative weight for social pillar

Indicators	Community facilities	Culture	Form and space	Stakeholder engagement	Health & wellbeing	Transport
Community facilities	0.07	0.10	0.03	0.08	0.04	0.08
Culture	0.03	0.05	0.03	0.08	0.01	0.08
Form & space	0.14	0.10	0.07	0.08	0.02	0.08
Stakeholder engagement	0.07	0.05	0.07	0.08	0.06	0.08
health & wellbeing	0.21	0.35	0.33	0.15	0.02	0.08
Transport	0.48	0.35	0.47	0.54	0.84	0.58
Sum	1.00	1.00	1.00	1.00	1.00	1.00

Table C.1(c): Eigen value calculations for social pillar

Core indicators	Community facilities	Culture	Form and space	Stakeholder engagement	Health & wellbeing	Transport	Eigen value
Community facilities	0.07	0.10	0.03	0.08	0.04	0.08	0.0670
Culture	0.03	0.05	0.03	0.08	0.01	0.08	0.0486
Form & space	0.14	0.10	0.07	0.08	0.02	0.08	0.0814
Stakeholder engagement	0.07	0.05	0.07	0.08	0.06	0.08	0.0676
health & wellbeing	0.21	0.35	0.33	0.15	0.02	0.08	0.1922
Transport	0.48	0.35	0.47	0.54	0.84	0.58	0.5432
Sum	1.00	1.00	1.00	1.00	1.00	1.00	

λ_{max}= (14.5 × 0.06703) + (20 × 0.0486) + (15 × 0.0814) + (13 × 0.10676) + (8.3 × 0.1922) + (1.7 ×0.5432) = 6.57

Hence $CI = \frac{(6.57-6)}{(6-1)} = 0.115$ (Using equation 5.6)

And subsequently

$CR = \frac{CI}{RI} = \frac{0.115}{1.24} = 0.09$ (Using equation 5.5)

Table C.2(a):Economic pillar reciprocal matrix

Core indicators	Facilities management	Governance and reporting	Economic effect	Employment and skills	Site selection	Procurement	Equality
Facilities management	1.0	2.0	2.0	0.3	1.0	2.0	0.33
Governance reporting	0.5	1.0	2.0	0.3	2.0	2.0	0.33
Economic effect	0.5	0.5	1.0	0.3	2.0	2.0	0.33
Employment and skills	3.0	3.0	3.0	1.0	1.0	2.0	3.00
Site selection	1.0	0.5	0.5	1.0	1.0	1.0	0.33
Procurement	0.5	0.5	0.5	0.5	1.0	1.0	0.20
Equality	3.0	3.0	3.0	0.3	3.0	5.0	1.0
Sum	9.50	10.50	12.00	3.83	11.00	15.00	5.53

Table C.2 (b): Normalized relative weight for economic pillar

Core indicators	Facilities management	Governance and reporting	Economic effect	Employmen t and skills	Site selection	Procurement	Equality
Facilities management	0.11	0.19	0.17	0.09	0.09	0.13	0.06
Governance reporting	0.05	0.10	0.17	0.09	0.18	0.13	0.06
Economic effect	0.05	0.05	0.08	0.09	0.18	0.13	0.06
Employment and skills	0.32	0.29	0.25	0.26	0.09	0.13	0.54
Site selection	0.11	0.05	0.04	0.26	0.09	0.07	0.06
Procurement	0.05	0.05	0.04	0.13	0.09	0.07	0.04
Equality	0.32	0.29	0.25	0.09	0.27	0.33	0.18
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table C.2 (c): Eigen value calculations for economic pillar

Core indicators	Facilities Management	Governance and Reporting	Economic Effect	Employment and Skills	Site Selection	Procurement	Equality	Eigen Value
Facilities Management	0.11	0.19	0.17	0.09	0.09	0.13	0.06	0.1191
Governance Reporting	0.05	0.10	0.17	0.09	0.18	0.13	0.06	0.1110
Economic Effect	0.05	0.05	0.08	0.09	0.18	0.13	0.06	0.0923
Employment And Skills	0.32	0.29	0.25	0.26	0.09	0.13	0.54	0.2684
Site Selection	0.11	0.05	0.04	0.26	0.09	0.07	0.06	0.0962
Procurement	0.05	0.05	0.04	0.13	0.09	0.07	0.04	0.0666
Equality	0.32	0.29	0.25	0.09	0.27	0.33	0.18	0.2465
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	

λ_{max}= (9.5 × 1191) + (10.5 × 1110) + (12× 0.0923) + (3.83 × 0.2684) + (11 × 0.0962) + (15 ×0.0666) + (5.53× 0.2465) = 7.85385

Hence $CI = \frac{(7.85385-7)}{(7-1)} = 0.1422$ (Using equation 5.6)

And subsequently

$CR = \frac{CI}{RI} = \frac{0.1422}{1.32} = 0.10$ (Using equation 5.5)

APPENDIX D: SPeAR® GUIDED QUESTIONS

Table D.1: Environmental indicators and guiding questions applied on case studies

Core Indicator	Sub-indicator	GUIDE QUESTIONS: WILL THE PROPOSED PROJECT HELP TO …
Soil and land	Contaminated land	• Affect the land (soil and water) may be contaminated due to past or present uses, or natural sources of contamination? • The site been assessed and investigated and judged not to be contaminated if there is potential for contamination, has? • Site if contaminated, has sufficient remediation (treatment/ containment/ cover) or other mitigation been undertaken. Is there the potential for harm to human health, pollution of the environment (water resources) or harm to ecological receptors, either on-site or off-site? • Site if contaminated, has sufficient remediation (treatment/ containment/ cover) or other mitigation been undertaken? • Give consideration to the effectiveness and durability of the remedial solution, and maintenance and monitoring over the lifetime of the project and beyond, and operational information conveyed to the operator?
	Soil quality	• Ensure that indigenous soil is protected during the construction/operation and decommissioning phases of project and there are good practice procedures in place for soil replacement? • Minimise erosion and control sediment? • The soil been treated in any way? • Place robust soil management plans? • Enhance ecosystem services provided by soil, including: - biomass production- storing, filtering and transforming nutrients and water/ hosting the biodiversity pool/acting as a platform for most human activities- providing raw materials/acting as a carbon sink/storing geological and archaeological heritage?
	Drainage systems	• Use sustainable drainage systems and green drainage infrastructure, including infiltration, bioswales, rain gardens, etc.? • Storm water management features been incorporated into a site-wide system(e.g. green roofs, retention ponds, rainwater collection, etc.)? • The project's drainage system appropriately manages the risk of site run-off to downstream properties? • Consider the use of both rainwater and greywater resources? Infiltration, rainwater harvesting.
Biodiversity	Protected	• Avoid negative effects on protected species and habitats?

	species and habitat	• Consider measures to minimise unavoidable effects to protected species and habitats? • Conserve and enhance the use of protected areas by local communities and for biodiversity? Is there evidence that the implementation of protected species and habitats recommendations is being monitored? • Respond to local biodiversity or conservation priorities? • Protect species and habitats incorporated into construction management plans?
	Conserving and improving local biodiversity	• Result in the loss of urban or rural biodiversity? • Taken measures to minimise losses of local biodiversity? • Have appropriate measures that enhance local biodiversity been included within the project? • To provide a landscape management plan in place that establishes the maintenance regime for the project's green spaces to support biodiversity objectives?
Waste	Designing out waste	• The design team to consider the need to reduce potential waste arising through design? • design process to consider designing for: Reuse and recovery/Offsite construction/ Waste efficient procurement/Deconstruction and flexibility • Produce a Site Waste Management Plan (SWMP) during the design phases of the project (e.g. LEED Materials & Resources, Construction Waste Management)? • Design waste collection areas to appropriate standards (e.g. British Standards BS: 5906)?
	Construction waste management plan	• Follow a waste hierarchy for construction waste management? • Have a construction waste strategy in place? • The waste minimisation plan set targets to reduce, re-use and/or recycle waste, and is it actively monitored for the duration of the project? • Include appropriate procedures to reduce waste produced and minimise waste to landfill in management plan? • Provide procedures for appropriate monitoring of waste? • Minimise construction waste through efficient material selection? (E.g. through supply chain, take back schemes, and just in time delivery.) • Minimise waste to landfill, including through re-use of waste on site and recycling? • The client/contractor have a commitment to a registered benchmarking programme (e.g. LEED, BREEAM, GreenStar, WRAP NetWaste?)?
	Waste in operation	• Provide operational waste strategy in place to manage and monitor, and reduce waste? Has an audit been completed with annual follow-ups to check progress? • Consider alternative waste collection methods? (e.g. Automated Waste Collection Systems)
	Hazardous/spec	• Produce hazardous/ special waste?

	ial waste	• The construction waste strategy try to reduce the level of hazardous waste (e.g. through material selection)? • Identify hazardous waste that arises as a result of land contamination or demolition of buildings been as well as being, minimised and managed? • Store hazardous waste separately, labelled and secured? • Provide appropriate management mechanisms in place (e.g. permits and specialist contractors)? Is this being monitored and reported? • Register the site as hazardous waste producer based on local regulatory requirements.
Materials	Materials efficiency in design	• Consider the need to minimise overall material consumption and use materials efficiently in the design process? • Critically assess material properties against their performance requirements? (The assessment might cover durability, maintenance, and mass, speed of construction, strength, and appropriate design-life.) • Specify materials in the contract such that the contractor is encouraged to implement recommendations?
	Use of recycled or reused materials	• Consider reused, recycled or secondary materials been sought and assessed for potential use? • Provide a materials inventory to enable future reuse of materials? • Enable future re-use or recycling of materials?
	Environmental and sustainability impacts of material	• Select materials to minimise environmental and sustainability impacts? (This can be done through use of an appropriate material rating system(e.g. the UK's BRE Green Guide to material specification or similar) or a lifecycle assessment, using a tool such as GABi) • Demonstrate the use of appropriate indicators (e.g. embodied CO2) to evaluate and improve the environmental (embodied) impact of materials in the design? Has the transport of materials been considered and applied to materials selection and specification? • Involvement of suppliers and contractors at a sufficiently early stage to allow options to be investigated adequately and specifications changed as a result?
	Healthy materials	• Consider the toxicity of materials used on the project? • Having an impact due to the materials selected on the indoor air quality (e.g. selection of low VOC finishes, paints, varnishes, sealants, flooring, glues) (see, for example, Green Seal certified materials, South Coast Air Quality Management District (SCAQMD) Rules, etc.)? • Consider the health impact of materials for the manufacturers, construction workers and project occupiers? • Prepare an Air Quality Management Plan to ensure mitigation of air quality risks during construction and before occupancy (e.g. appropriate materials storage to avoid damp, Minimum Efficiency Reporting Values for ventilation, etc.)?
Water	Water pollution	• Identify the potential sources of water pollution either resulting from existing land uses, the proposed project or

		in the source water for the project (e.g. industrial discharges in the vicinity of the abstraction point)? • Identify the sensitivity of the receiving water environment been assessed? • Consider if the project been designed to avoid the discharge of pollutants to surface and ground water?
	Water resources	• Does the project lie within a water scarce area or is it under water use restrictions? • Quantifying the extraction capacity of the water resource/ aquifer? • Affect the availability of water from the resource/aquifer? • Consider the impact of water use on other users and ecosystems? Have measures been incorporated in the project that will allow long-term monitoring of the project's impact on the water environment? • Provide opportunities to improve the local water environment been included in the design and implementation?
	Waste water treatment Disposal	• Consider alternate disposal methods for wastewater in the project planning (either on-site or off-site) (e.g. reedbed filtration system, Living Machines, bioreactor, etc.)? • Identify methods for the disposal of residual wastes from wastewater treatment facilities? • Bring opportunities within the project to educate the local community about the wastewater cycle in relation to alternate treatment methods utilised on the project and how it can affect human health and the environment? • Explore options that look at the opportunity for linking wastewater treatment to energy generation?
	Water monitoring	• Install meters and sub-meters for water use monitoring? • Building management system and environmental management system include water use monitoring? • Plan (and targets) to manage and reduce water use and water loss? • Install leak detection sensors in to pipe work and building systems?
	Water supply	• Have a hierarchy of options been considered as water sources?2. Does the design minimise mains potable water consumption? Have options been explored that reduce the energy intensity and carbon footprint of water supply (e.g. through reductions in unnecessary treatment and pumping)?
	Construction	• Consider a sustainable source on the site that could be used (e.g. rainwater, greywater, and borehole)? What is the water source for construction water? • Determine a sustainable yield rate?
Energy demand	Energy supply	• Consider renewable energy sources for use in the construction phase? • Consider renewable energy generation technologies for use in the operational phase? Is the supply on-site or near-site? • Commitment of the development to the purchase of registered green electricity tariffs (e.g. for the US, Green-e certified sources)? • Purchase Renewable Energy Certificates (RECs) or participate in offsetting for the construction or operational

		phase? • Give consideration if the project produces residual heat, how this could be used elsewhere?
	Energy conservation and efficiency	• Reduce overall energy demand? • Prepare an energy model? • Consider operational energy efficiency of the project been as a key consideration during the design? • Maximise use of passive lighting, heating and cooling (e.g. through building siting, orientation, layout and form)? • Take measures to reduce energy consumption included within the project, including from lighting, heating, ventilation and cooling, and appliances • Use of different construction processes reduce energy usage? • Influence procurement, maintenance and use of construction plant been by consideration of their energy efficiency, energy type or carbon emissions? • Consider efficient energy supplies, such as combined heat, power and cooling, and district energy networks?
	Energy monitoring	• Include energy use monitoring in project's environmental management system? • Install meters and sub-meters installed for targeted energy monitoring? • Integrate meters and sub-meters as part of the building management system? • Have plans (and targets) in place to manage and reduce energy use? Do energy reduction plans have a clear owner, who is empowered to deliver? • Consider real-time energy monitoring and display systems been?
	Daylighting	• Use natural light be used instead of artificial light during daylight hours? • Introduce daylight controls in the design to reduce the need for artificial lighting when natural light is available? • Design day lighting to avoid solar glare and unwanted heat loading (e.g. through appropriate shading strategies)?
Climate change	Carbon management plan	• Develop a carbon management plan, including plans to reduce emissions arising as a result of the project's construction and operation? • Cover carbon equivalent emissions (including all greenhouse gases associated with the project, plus use of refrigerants with global warming potential) in the management plan? • Establish clear reduction targets? • Complete a lifecycle carbon assessment plan for the project (construction, operation, end-of-life)? Does the management plan cover scope 1, 2 and 3 emissions (direct and indirect emissions)?Does the management plan include a targeted, flexible monitoring plan?
	Social impact	• Identify the potential impacts of climate change on the project and local community?

	of climate change	• Consider and address the likely effects of climate change on local communities and in particular disadvantaged communities? • Take adaptation measures to address future wear and tear on current facilities and to lessen the impacts of possible extreme weather events (e.g. extreme heat or cold, storm events, high winds, snowfall, as applicable to the geography)? • Consider the potential impacts of damage to locally important infrastructure (e.g. energy supplies, water mains, transport networks, etc.)? Is the project resilient to such future shocks? • Be designed to be flexible, so that it can be adapted to a changing climate over time? Are there opportunities to retrofit new infrastructure?
	Physical impact of climate change	• Identify the potential impacts of climate change on the project and the local built and natural environment? (Including fires, water scarcity, heat waves, soil degradation, subsidence, storm damage, etc.)? • Consider and addressed the likely effects of the project? • Provide a water resource and flood risk assessment and take into account the impacts of climate change, been carried out by a qualified engineer? • Complete geological assessments by a qualified engineer, to determine future risks of subsidence in light of climate change? • Design the project to be flexible, so that it can be adapted to a changing climate over time?
	Economics of climate change	• Give consideration to the immediate cost of action to mitigate possible climate change impacts versus the long-term costs of inaction? • Consider risks related to the impact of climate change on economic development and key sectors in the context of the project? • Consider the broader economic opportunities presented to the project? Is there an opportunity to gain first mover advantage, by anticipating future demand for climate resilient development? • Consider the impact of climate change for business continuity of occupants or users?
Air quality	Ambient air quality	• Consider the local ambient air quality in the design of the project? • Consider if the ambient air quality likely to affect occupiers/ users of the project? • Ensure air quality been considered in the design of ventilation strategies? • Ensure if there are any significant local air pollution sources and if so, where are they located in relation to the proposed project?
	Direct emissions	• Consider if the project has an impact on the ambient air quality management strategy for the local area? • Assess if the project been designed to minimise human and flora/fauna exposure to air pollutants?

		• Measure if the direct emissions from the facility/ies been identified and is the effect on these emissions on ambient air pollutant concentrations understood? • Consider if targets been set to reduce emissions?
	Indirect emissions	• Assess if the indirect emissions from the project been identified (including those related to transportation) and is the effect of these emissions on ambient air pollutant concentrations understood? • Consider what does the fuel type(s)/mix to be used for energy generation / transportation?

Table D.2: Social indicators and guiding questions applied on case studies

Core indicator	Sub-indicator	GUIDE QUESTIONS: WILL THE PROPOSED PROJECT HELP TO …
Community facilities	Education	• Facilitate local communities 'access to high quality, affordable educational facilities in the vicinity? • Include provision of education facilities where appropriate? • Enhance and link with organisations providing high quality and affordable skills and vocational training available locally?
	Health centres	• Improve or provide for a local health care facility, which offers affordable medical care to all groups? • Consider the availability of funding to run the healthcare programme? • Does the project put strain on existing health facilities?
	Recreation	• Improve or provide local recreational facilities, including, e.g. indoor and outdoor leisure facilities, green spaces and cultural facilities? • Facilitate local communities 'access to high quality, affordable recreation facilities in the vicinity? • Provide space for or actively promote groups or activities?
	Retail	• Either provide new retail facilities available to the local community, or ensure that existing facilities are easily accessible? • Existing local retail businesses to be negatively affected by the project?
Culture	Cultural and religious facilities	• Has an assessment been undertaken of built and natural facilities, which promote the unique natural and/or religious aspects of the local community? • Provide or enhance appropriate cultural or religious facilities where there is an identified need? • The project to be equally accessible to people from all cultural and religious groups within the community?
	Use of environment	• Integrate the use of existing natural or human-made features in the local environment (e.g. spring sources, topography, and flood banks)? • Accommodate both new as well as existing practices where appropriate (e.g. livestock watering, clothes washing, local architectural styles and crafts)?
	Archaeology and local heritages	• Archaeological issues associated with the site if there is any? Or historical and listed heritage buildings or monuments on the site? If so, how are they being assessed, protected or enhanced as a part of the project? • The heritage conservation area if site is in any? • Enabled the retention, restoration and successful re-use integration of historical and listed buildings/or monuments into the project?

		• Historic environment assets (whether listed, schedules, registered or no to be demolished or removed, has an appropriate mitigation design been developed and agreed with the relevant conservation regulator? • Explore opportunities been to dismantle, relocate and re-purpose historic buildings and infrastructure, as an alternative to demolition?
	Art	• Public art being used to make the public realm more attractive? • Reflect local culture using art effectively? • Leveraging art to enhance safety, security and usability of public spaces (e.g. for climate comfort, lighting, etc.)?
Form and space	Density, scale and, depth & massing	• Provide appropriate development density/scale and depth to the surrounding area, and aligns with objectives for green open space?
	Public, private and communal spaces	• Provide clear definition and transition between public and private space? • Provide main entrances clearly visible from publicly accessible areas to enhance security through public surveillance? • Private areas screened to ensure appropriate privacy?
	Security	• Allow good open visibility with minimal dark or hidden areas? • Providing clear definition between public and private areas? • Providing opportunities to increase the mix of use to encourage greater activity at varying times of the day at night? • Public areas to appropriately lit to deter anti-social behaviour and improve perceived levels of safety, whilst minimising trespass of light to surrounding areas? Has appropriate design guidance been adopted, e.g. secured by design, Crime, prevention through environmental design, etc?
	Connectivity	• Improve connectivity between existing communities and facilities? • Fragment communities, or make access to key facilities more difficult? • Improve connectivity between existing communities and rural hinterland and open space?
Stakeholder engagement	Identification and analysis	• Provide a systematic process for identifying and analysing both direct and indirect stakeholders? • Have stakeholders been identified, whose voices are typically under-represented in decision-making processes? Are efforts being made to include these people in discussion?
	Stakeholders participation and consultation	• Consider the level of involvement of stakeholders in the process (information only, consultation, participation) been considered and participation prioritised? • Start the process as early as possible to avoid miscommunications about the project's content and intentions,

		and to encourage meaningful input into the design? • Integrate stakeholder consultation and participation been into the project delivery team processes with regard to resourcing, scheduling, allowance for feedback and dialogue? • Provide a feedback mechanism in place that is easily accessed by stakeholders and through which stakeholders can expect a prompt response? • Include a mechanism by which stakeholders can take their concerns to a third party if they feel that the initial grievance process is not responding to their concerns? • Incorporate stakeholder concerns and opinions being actively into design, operation and project management decisions? Are there measures in place that make it sufficiently clear what is being consulted on and where there is scope for influence from the stakeholders? Have decisions on the project been taken jointly with stakeholders? Have stakeholders influenced the design of the project and decisions relating to it?
	Integrating stakeholders' comments	• Incorporate stakeholder concerns and opinions into design, operation and project management decisions? • Make it sufficiently clear what is being consulted on and where there is scope for influence from the stakeholders? • Ensure decisions on the project been taken jointly with stakeholders? • Ensure Stakeholders influenced the design of the project and decisions relating to it?
Health and wellbeing	Access to green space	• Provide green space by the development? Is the quality of local space improved? • Improve access to green space? This could be achieved through creation of access points, improving the quality of the green space, education, and signage and improving safety. How will the space be manage and maintained?
	Community cohesion	• Increase the integration between different groups and communities? • Encourage positive dialogue between local community groups, including those who may have previously had little interaction? • Meet the needs of both existing communities and potential newcomers to avoid tensions, e.g. over competition for natural resources, housing, jobs? • Recognise the needs of different individuals and community groups?
	Institutions and social networks	• Improve the linkages of local communities and disadvantaged groups with governmental and non-governmental institutions and services? • Strengthen or preserve informal social networks within local communities and disadvantaged groups?
	Indoor environment	• Create a pleasant internal environment for occupants and users? • Consider the spectrum of comfort issues c, including: odour, noise, vibration, airborne pollutants, traffic

		generation, greenery/plants, light and thermal comfort? • Users/ occupiers to have appropriate levels of control over their immediate indoor environment?
	Social vibrancy	• Provide appropriate spaces for people to meet and socialise? • Ensure that all members of the community can benefit from the opportunities for social activity and community participation of the place? • Design and programming for active spaces reflect the needs of the local communities? • Ensure the proposed programming activation of public spaces at all times of the day, providing a lively social arena?
Transport	Public transport infrastructure	• Integrate pubic transport infrastructure into the project? If yes, how far is the public transport infrastructure from the site in terms of minutes walking? And is it easy for public transport to be used at the necessary times? • Provide public transport service appropriate/useful destinations? Is integration provided between transport networks to allow mode change (e.g. bus to train)? • Provide affordable public transport? • Consider alternative vehicle types and fuels? • Make provision to create new links to existing public transport, rather than relying on private motor vehicles if the project is not located near existing public transport links? Has the local public transport provider been consulted?
	Pedestrian design and facilities	• Create a well-connected, comfortable and attractive pedestrian environment to encourage walking by all members of the community regardless of age or ability, both within and to/from site? • Design the pedestrian routes to be safe at all times of day, with appropriate lighting, surveillance and separation from bicycle/vehicles? • Design the project to make it quicker to walk than drive for short journeys? • Provide information such as appropriate pedestrian a signage and wayfinding information, both along trails and via smart phones, internet,etc? • Connect pedestrian routes with recreational walking trails in the surroundings area, encouraging walking for health as well as functional reasons?
	Cycle design and facilities	• Create a well-connected, attractive and safe environment for people of all ages and abilities to cycle? • Provide facilities (e.g. changing rooms, secure cycle parking) for those who cycle? • Design to make it quicker to cycle than drive for short journeys? • Provide Bicycle share facilities? • Connect cycle routes?

	Waterways	• Locate the project near any navigable waterways, or are any waterways upgraded to be navigable as part of the project? • Use waterways for freight journeys where possible? • Provide journeys by boat to be easy and accessible to all? • Does water transport serve appropriate/useful destinations? • Consider the use of alternative fuels?
	Freight traffic	• Consider the percentage of freight traffic by rail or waterway transport versus road? • Incorporate freight consolidation centres to reduce movement of large vehicles? • Consider low emission vehicle technologies been considered for freight transport?
	Low emission vehicles	• Encourage the use of low emission, e.g. by providing charging infrastructure? • Encourage low emission vehicles actively, e.g. through variable charging or priority parking? • Provide alternative fuel infrastructure by the project linked to a wider network?
	Private vehicle use	• Provide for sustainable modes to make private vehicle use the least attractive option? • Minimise car parking required? Have local authorities been engaged in objectives to reduce parking provision below local zoning requirements? Is car parking prioritised for those with disabilities, essential users, car clubs, car sharers and alternative fuel vehicles? • Deprioritise in the development layout, making it less attractive than other modes?
	Air travel	• Encourage alternatives to air travel, particularly for short trips (e.g. provision of high-technology video-conference facilities)? • Encourage the use of low emission / renewable fuels been considered?

Table D.3: Economic indicators and guiding questions applied on case studies

Core indicator	Sub-indicator	GUIDE QUESTIONS: WILL THE PROPOSED PROJECT HELP TO …
Facilities management	Usability	• Design the system with the end-user/occupier in mind and tested where appropriate? • Specify easy-to-use systems wherever possible? • Has the end-user/occupier been consulted through the building design process? • Prepare a building user manual, training or handover plans to support building use?
	Appropriate technologies	• Use technologies which are suitable for the local context and which can be readily and cost-effectively maintained using locally available skills, tools and parts? • Where technologies are, by necessity, new to the context: Include the necessary training and development to ensure a local capacity to install, operate and maintain the technology in the project?
	Whole life flexibility	• Consider flexibility over the project's lifetime considered as part of the design criteria (e.g. minimum refit requirements, reuse and recyclability of components)? • Have adaptable building systems to changing environmental, social and economic conditions (e.g. climate change, demographic change, consumer preferences)?
	Operation and maintenance	• Identify and cost maintenance and operation requirements of the project (e.g. including highways, green spaces, community facilities, buildings, energy systems)? Is there full provision for these costs in the financial appraisal? • Assign responsibility for the operation of each of the facilities? Has the capability of the operating authority to manage and maintain the asset been assessed, in terms of both skills and available finance? • Integrate an assessment of the capacity of users to pay for services been into studies of financial viability? • Provide evidence that long-term planned maintenance has been considered in the design process? • Provide maintenance plans been prepared for building systems, landscaping, etc.?
Governance and reporting	Monitoring and evaluation	• Place a performance monitoring system, including a comprehensive set of performance indicators covering the project's key areas of impact? • Assign responsibility for monitoring to a named individual or role? Are performance indicators relating to the impact of the project on the community and affected ecosystems included in the monitoring and evaluation process? • Meet all the monitoring and evaluation systems the needs of all project stakeholders? • Involve local stakeholders in performance monitoring and make the outcomes of monitoring freely available to

		stakeholders in a timely and useful way? • Fund long term monitoring? Is it clear who will take responsibility for monitoring and evaluation and how the outputs will be acted on? Will the results of post-occupancy monitoring be used to inform future design and development works?
	Information disclosure and reporting	• Ensure, comprehensive reports produced documenting project sustainability performance (e.g. newsletters, website updates, social media, public events, etc.)? • Ensure the information communicated in a manner appropriate to local stakeholders (i.e. in a language, format and choice of medium that they can easily understand)?
	strategy	• Enclose a comprehensive sustainability strategy in place? • Included strategy contain actions and is the responsibility for delivering these actions clearly defined? • Implementation of the strategy to be funded? • Included strategy take advantage of all financial incentives and partnerships that can make sustainability initiatives cost-neutral to the project? • The strategy to take a joined-up approach to delivering sustainability across all topic areas?
	Risk management	• Include a dedicated process in place for risk assessment, review and monitoring, in accordance with the requirements outlined in ISO 31000:2009? • Assign responsibilities for managing risk been assigned within the project delivery structure? Have risk owners been allocated to each risk? • Identify all categories of risk - including financial, political, economic, social, reputation, regulatory and environmental risks? Has a positive risk management framework, been used?
	Donations to voluntary and community organisations	• Make (financial and non-financial) to relevant voluntary and community organisations? (Donations may be financial, gift-in-kind or employee volunteering.) • Consider what percentage of capital expenditure or pre-tax profits is being donated? • Ensure long-term relationships, partnerships and programmes in place? • Assess donations make the best use of the project's skills and experience and address the issues of most importance to the community?
Economic effect	Value for money	• Consider value for money (as distinguished from lowest cost), part of the criteria for appraisal of the economic performance of the project? • Develop a detailed understanding of the costs and benefits associated with the project over the entire lifecycle and the likely persistence of these benefits once the project is fully operational?

		• Consider wider economic benefits and non-monetary costs and impacts been considered? • Have the lifecycle costs of sustainability initiatives been calculated, to determine potential operational savings as balanced against capital investment?
	Distortions to local economy	• Present potential negative impacts for the local economy, particularly for low income or minority individuals/groups? Key issues to consider include: major population influx; inflation; competition for local jobs/services/utilities; unsustainable use of local natural resources; impacts on traditional land rights, occupations and production systems; unsustainable competition effects for existing local businesses, small-/medium-sized enterprises or minority-owned businesses. • Procure local goods, services and labour? Has the amount of money to be spent in the local economy been determined? • Consider the expected leakage of income, displacement, deadweight loss and multiplier effects been calculated to identify the net additional impacts? • Consider management strategies in place to mitigate potential negative impacts on such local distortions?
	Vitality and regenerations	• Considers-economic baseline assessment of the local area been undertaken and are the findings used to shape the project to address weaknesses and opportunities? • Consider sectoral profiles of local industries, local and project supply chains been undertaken and the impact of the project considered on them? • Promote a diversification of employment types? If not could the project encourage a more effective use of technology, innovation, people and skills and hence the increased value added captured by local firms and society? • Sustainable businesses been explored? • Businesses operating to their full potential? That is, are they effectively employing all available technology and knowledge to produce quality goods and services?
	Carbon pricing	• Have the implications of a future cost of carbon been considered for the project? • Has a cost or shadow price of carbon been incorporated in to the project financial appraisals?
Employment and skills	Labour standards	• Provide wages to those involved in the project be sufficient to provide for a basic standard of living in the region where they live? • Provide robust systems for managing health and safety in workplaces associated with the development? • Put systems in place to ensure there is no forced, illegal and/or child labour on the project or in the project supply chain? • To put systems in place to ensure workers' rights for freedom of association and collective bargaining are upheld?

	Employment creation in construction	• Prioritise labour-based, rather than capital-based technology in construction? • Ensure that local people benefit from job opportunities provided by the project? • Sustain local employment opportunities once the project has finished? • Equip local supply chain to supply the necessary goods and services during construction? • Give opportunity to local people to benefit from the employment creation?
	Employment creation in operation	• Ensure? e the jobs provided long-term (i.e. 2 yrs +)? • Ensure local people given the opportunity to benefit from the employment creation? • Improve labour-based technology used to maximise the number of jobs created?
	training	• Include training activities for local workers if it is necessary? • Take measures if there is a shortfall in local capacity to maintain and operate the project, to address these skills gaps? • Take opportunities to deliver training activities through local service providers?
	Access to finance	• Provide affordable finance for local entrepreneurs and enterprises? • Are there providers of micro credit or development finance within the region (if applicable)? • Are there actions that the proponent can take to facilitate access to affordable finance?
	Social mobility	• Are opportunities created for local people at a range of skills levels and types? • Is training provided in order to help the local workforce improve its skills?3. Are skills required for delivering the project that are not currently available locally and are there opportunities to train local people rather than bringing in skills from elsewhere?
Site selection	Site location	• Whether the site in use prior to the proposed project, or is it on undisturbed land? If located on undisturbed land, was an assessment made of whether the development could have been located on an alternative previously-used site? • Minimise Negative impacts on communities and areas of ecological importance? • Adversely affect the site at risk from natural hazards due to project location, or its access, power supply or water supply (e.g. landslide, subsidence, earthquakes or flooding)? • Serve the site by existing public transportation networks? If not, could existing networks be expanded to serve the site? • Provide key facilities (retail, banks, post office, etc.) within walking distance of the site?
	Planning intent	• Assess if there any land use designations associated with the proposed project location (e.g. built heritage, zoning requirements, etc.)?

		• Consider if the proposed project in conformance/compliance with relevant local/regional/national planning requirements for the site? • Consider if the project's performance improves on the sustainability of what is legally required in terms of land use objectives, zoning requirements and building codes?
	Diversity/mixed use	• Provide a variety of basic services and facilities provided by the project? • Contribute to the diversity of facilities and services in the local area? • Provide access to these facilities for all local residents (e.g. at off-peak times or out of hours for schools, etc.)?
Procurement	Local sourcing	• Consider local availability of materials, skills, goods and services during planning and design, and used to inform the design specification? • Analyse construction/ operational supply chains in terms of the tiers of separation between source and end-user, geographical distance over which goods must travel; or delivery times involved? • Introduce opportunities to prioritise local suppliers through project procurement? • Provide opportunities or support for community suppliers, social enterprises, Small- and Medium-sized Enterprises, or businesses certified Minority-owned, Women-owned or disadvantaged? Is their potential to increase the role of these groups in project delivery?
	Global sourcing	• Include policy on sustainable procurement, responsible sourcing, or a code of ethical conduct applicable to supply chains? Are principles of fair trade, international labour rights and environmental stewardship considered through these policies? • Consider sustainability performance of supply chains monitored, audited and reported?
	Procurement strategy	• Provide a project-specific sustainable procurement strategy in place, which covers all design, construction and operational procurement functions? • Define clear actions and responsibilities and allocate resources in strategy? Are actions joined up to ensure a mutually supportive approach to procurement is adopted by all members of the team? Is the strategy signed off by senior management? • the sustainable procurement strategy clearly support the sustainability goals, objectives and targets for the project as a whole, linking with the overall sustainability strategy, environmental management plan and socio-economic assessments? Are issues included with respect to local sourcing, global supply chains and embodied impacts of materials? • Provide guidance with respect to balancing cost against other criteria? • Rolled out/communicated the strategy to the design team members and other relevant stakeholders? Has training been provided to procurement staff? Does the strategy provide a procedure for monitoring and

		reporting sustainable procurement practices?
Equality	Affordability	• The project meet the needs of local low-income people or minority groups? • Project result in improved quality of life for all in the local community, regardless of socio-economic status? • What proportion of the project will be affordable to low and very-low income groups?
	Designing for equality	• Provide an assessment of the adverse effects that project implementation could have on equality groups (including on grounds of ethnicity, gender, race, religion, sexual orientation, age, disability, social background, nationality, marital status, mental health and illness)? • Adversely affected indigenous, low-income, and other vulnerable populations that might be during the development and implementation of the project? • Issues of disability and accessibility been considered during the design, construction and operation stages? • Seek to remove barriers to opportunity, especially for disadvantaged groups?
	Impacts and benefits	• Carry out social, economic and environmental impacts for the project? If so, were all key stakeholders involved and adequately represented? • Identify to mitigate negative impacts? Is there a process to implement these strategies? Who will pay for or subsidise the project and its operation, and are these costs equitably and fairly distributed?
	Land tenure	• Resolve and clearly define land tenure? • Provide options for the proponent to support the positive resolution of issues relating to land tenure? Have these options been identified and adopted by the proponent?
	displacement	• Affect relocation of populations and being displaced? • Have a resettlement plan and grievance mechanisms in place if Involuntary relocation/displacement, does the project team?

APPENDIX E: COST DETAILS

Table E.1: Energy alternative cost analysis

	Cost					Lifecycle cost				Benefits		
Items.	**Description**	**Unit**	**Amount**	**Unit Price**	**Net Total**	**Product Lifecycle (years)**	**No. of times item requires to be replaced**	**Required amount**	**Cost of replacement for each time**	**Items.**	**Description**	**Net Total**
Energy												
1	**Energy supply**										**Energy supply saving within lifetcycle of building**	
1.1	Large off-grid solar power system	No.	10	£10,000.00	£100,000.00	15	1	10	£100,000.00	1, 2	Total Green energy supply saving based on 30 year building lifetime	£6,000,000.00
1.2	LED Lights	No.	400	£30.00	£12,000.00	3	9	400	£12,000	3	Using "Advanced Energy Monitoring System" (AEMS)	£3,000,000.00
1.3	Cable 5 mm	m	1,500	£1.50	£2,250.00	15	1	1,500	£2,250.00	4	Saving due to using advanced sustainable cooling and heating system	£2,750,000.00
1.4	Cable 10 mm	m	1,500	£10.00	£15,000.00	15	1	1,500	£15,000.00	5	Saving due to using low maintenance material and design approach	£10,500,000.00
1.5	Cable 15 mm	m	1,200	£20.00	£24,000.00	15	1	1,200	£24,000.00			
1.6	Cable 20 mm	m	500	£33.00	£16,500.00	15	1	500	£16,500.00			
1.7	Cable 25 mm	m	250	£55.00	£13,750.00	15	1	250	£13,750.00			
1.8	Cable 30 mm	m	200	£100.00	£20,000.00	15	1	200	£20,000.00			

1.9	BG Nexus 13A 2G DP Switched Socket	No.	130	£13.00	£1,690.00	15	1	130	£1,690.00			
1.10	BG Nexus 13 FCU w/ Neon	No.	40	£16.00	£640.00	15	1	40	£640.00			
1.11	Appleby 2G 35mm Dry Lining Box	No.	75	£1.20	£90.00	15	1	75	£90.00			
1.12	LAP Installation Boxes Galvanised Steel 2 Gang 25mm	No.	400	£5.00	£2,000.00	15	1	400	£2,000.00			
1.13	British General 13A 2 x 2-Gang Combination Plate Brushed Steel	No.	200	£26.00	£5,200.00	15	1	200	£5,200.00			
1.14	Greenbrook T205-SCR KingShield 7-Day Fused Digital Timer Spur Switch 230V	No.	40	£200.00	£8,000.00	15	1	40	£8,000.00			
1.15	MK 2-Gang RCD Active Switched Plug Socket Metal-Clad	No.	40	£105.00	£4,200.00	15	1	40	£4,200.00			

1.16	AP 13A 2-Gang DP Switched Plug Socket Brushed Stainless Steel	No.	450	£25.00	£11,250.00	15	1	450	£11,250.00			
1.17	Tower Maxi Trunking 50mm x 50mm x 2m	m	1,500	£40.00	£60,000.00	15	1	1,500	£60,000.00			
1.18	Conduit 20mm x 3m Black	m	1,500	£50.00	£75,000.00	15	1	1,500	£75,000.00			
1.19	MK Sentry 100A 21-Way Split Load Metal Consumer Unit & 2 x RCDs	No.	40	£240.00	£9,600.00	15	1	40	£9,600.00			
2	**Application of green and sustainable source of energy, (Research)**	Hours	500	£70.00	£35,000.00	30	0	0	£0.00			
3	**Energy monitoring**											
3.1	Energenie Energy Monitor Socket & Gateway Set	No.	50	£190.00	£9,500.00	15	1	50	£9,500.00			
4	**Cooling and ventilation**											
4.1	Central heating system	No.	5	£32,000.00	£160,000.00	15	1	5	£160,000.00			

4.2	RM Prostel Horizontal Indirect Unvented Hot Water Cylinder 250Ltr	No.	4	£1,000.00	£4,000.00	15	1	4	£4,000.00			
4.3	Piping accessories in total	No.	1	£100,000.00	£100,000.00	15	1	1	£100,000.00			
4.4	Pipe	m	2,000	£40.00	£80,000.00	15	1	2,000	£80,000.00			
4.5	Air condition	No.	25	£2,000.00	£50,000.00	15	1	25	£50,000.00			
5	**Labour**											
5.1	Labour cost for Installation	Hours	10,000	£80.00	£800,000.00	1	29	600	£48,000.00			
Total					**£1,619,670.00**						**Total**	**£22,250,000.00**

Table E.1.1: Energy alternative- Discount rate: 7.3%

Year	**Cost**	**PV (C_i)= $\frac{1}{(1+r_t)^t}C_{it}$**	**Benefit**	**PV (B_i)=$\frac{1}{(1+r_t)^t}C_{it}$**
year	cost	PV cost	benefit	Pv benefit
0	£1,619,670.00			
1	£48,000.00	£44,734.39	£1,112,500.00	£1,036,812.67
2	£48,000.00	£41,690.95	£1,112,500.00	£966,274.63
3	£60,000.00	£48,568.21	£1,112,500.00	£900,535.53
4	£48,000.00	£36,211.15	£1,112,500.00	£839,268.90
5	£48,000.00	£33,747.58	£1,112,500.00	£782,170.46
6	£60,000.00	£39,314.51	£1,112,500.00	£728,956.63
7	£48,000.00	£29,311.85	£1,112,500.00	£679,363.12
8	£48,000.00	£27,317.66	£1,112,500.00	£633,143.63
9	£60,000.00	£31,823.93	£1,112,500.00	£590,068.62
10	£48,000.00	£23,727.06	£1,112,500.00	£549,924.16
11	£48,000.00	£22,112.83	£1,112,500.00	£512,510.87
12	£60,000.00	£25,760.52	£1,112,500.00	£477,642.93
13	£48,000.00	£19,206.35	£1,112,500.00	£445,147.19
14	£48,000.00	£17,899.67	£1,112,500.00	£414,862.24
15	£832,670.00	£289,385.71	£1,112,500.00	£386,637.69
16	£48,000.00	£15,546.97	£1,112,500.00	£360,333.36
17	£48,000.00	£14,489.25	£1,112,500.00	£335,818.60
18	£60,000.00	£16,879.37	£1,112,500.00	£312,971.67
19	£48,000.00	£12,584.81	£1,112,500.00	£291,679.09
20	£48,000.00	£11,728.62	£1,112,500.00	£271,835.13
21	£60,000.00	£13,663.35	£1,112,500.00	£253,341.22
22	£48,000.00	£10,187.02	£1,112,500.00	£236,105.52
23	£48,000.00	£9,493.97	£1,112,500.00	£220,042.42
24	£60,000.00	£11,060.07	£1,112,500.00	£205,072.15
25	£48,000.00	£8,246.09	£1,112,500.00	£191,120.37
26	£48,000.00	£7,685.08	£1,112,500.00	£178,117.77
27	£60,000.00	£8,952.80	£1,112,500.00	£165,999.79
28	£48,000.00	£6,674.97	£1,112,500.00	£154,706.23
29	£48,000.00	£6,220.84	£1,112,500.00	£144,181.02
30		£0.00	£1,112,500.00	£134,371.87
Total		£884,225.58		£13,399,015.48
		NPV	£10,895,119.90	

Table E.1.2: Energy alternative- Discount rate: 8%

Year	Cost	PV (C_i)= $\frac{1}{(1+r_t)^t}C_{it}$	Benefit	PV (B_i)= $\frac{1}{(1+r_t)^t}C_{it}$
0	£1,619,670.00			
1	£48,000.00	£44,444.44	£1,112,500.00	£1,030,092.59
2	£48,000.00	£41,152.26	£1,112,500.00	£953,789.44
3	£60,000.00	£47,629.93	£1,112,500.00	£883,138.37
4	£48,000.00	£35,281.43	£1,112,500.00	£817,720.71
5	£48,000.00	£32,667.99	£1,112,500.00	£757,148.81
6	£60,000.00	£37,810.18	£1,112,500.00	£701,063.71
7	£48,000.00	£28,007.54	£1,112,500.00	£649,133.06
8	£48,000.00	£25,932.91	£1,112,500.00	£601,049.13
9	£60,000.00	£30,014.94	£1,112,500.00	£556,526.98
10	£48,000.00	£22,233.29	£1,112,500.00	£515,302.76
11	£48,000.00	£20,586.38	£1,112,500.00	£477,132.18
12	£60,000.00	£23,826.83	£1,112,500.00	£441,789.06
30	£48,000.00	£17,649.50	£1,112,500.00	£409,063.94
14	£48,000.00	£16,342.13	£1,112,500.00	£378,762.91
15	£832,670.00	£262,492.31	£1,112,500.00	£350,706.40
16	£48,000.00	£14,010.74	£1,112,500.00	£324,728.15
17	£48,000.00	£12,972.91	£1,112,500.00	£300,674.21
18	£60,000.00	£15,014.94	£1,112,500.00	£278,402.04
19	£48,000.00	£11,122.18	£1,112,500.00	£257,779.67
20	£48,000.00	£10,298.31	£1,112,500.00	£238,684.88
21	£60,000.00	£11,919.34	£1,112,500.00	£221,004.52
22	£48,000.00	£8,829.14	£1,112,500.00	£204,633.81
23	£48,000.00	£8,175.13	£1,112,500.00	£189,475.75
24	£60,000.00	£9,461.96	£1,112,500.00	£175,440.51
25	£48,000.00	£7,008.86	£1,112,500.00	£162,444.92
26	£48,000.00	£6,489.68	£1,112,500.00	£150,411.96
27	£60,000.00	£7,511.21	£1,112,500.00	£139,270.34
28	£48,000.00	£5,563.86	£1,112,500.00	£128,954.01
29	£48,000.00	£5,151.72	£1,112,500.00	£119,401.87
30		£0.00	£1,112,500.00	£110,557.28
Total		£819,602.06		£12,524,283.97
		NPV	£10,085,011.91	

Table E.1.3: Energy alternative Discount rate: 12.6%

Year	Cost	PV (C_i)= $\frac{1}{(1+r_t)^t}C_{it}$	Benefit	PV (B_i)= $\frac{1}{(1+r_t)^t}B_{it}$
1	£48,000.00	£42,628.77	£1,112,500.00	£988,010.66
2	£48,000.00	£37,858.59	£1,112,500.00	£877,451.74
3	£60,000.00	£42,027.74	£1,112,500.00	£779,264.42
4	£48,000.00	£29,859.85	£1,112,500.00	£692,064.32
5	£48,000.00	£26,518.52	£1,112,500.00	£614,621.95
6	£60,000.00	£29,438.85	£1,112,500.00	£545,845.43
7	£48,000.00	£20,915.70	£1,112,500.00	£484,765.03
8	£48,000.00	£18,575.23	£1,112,500.00	£430,519.57
9	£60,000.00	£20,620.81	£1,112,500.00	£382,344.20
10	£48,000.00	£14,650.66	£1,112,500.00	£339,559.68
11	£48,000.00	£13,011.25	£1,112,500.00	£301,562.77
12	£60,000.00	£14,444.10	£1,112,500.00	£267,817.74
13	£48,000.00	£10,262.24	£1,112,500.00	£237,848.79
14	£48,000.00	£9,113.89	£1,112,500.00	£211,233.38
15	£832,670.00	£140,409.68	£1,112,500.00	£187,596.25
16	£48,000.00	£7,188.31	£1,112,500.00	£166,604.13
17	£48,000.00	£6,383.94	£1,112,500.00	£147,961.04
18	£60,000.00	£7,086.96	£1,112,500.00	£131,404.12
19	£48,000.00	£5,035.14	£1,112,500.00	£116,699.93
20	£48,000.00	£4,471.71	£1,112,500.00	£103,641.15
21	£60,000.00	£4,964.15	£1,112,500.00	£92,043.65
22	£48,000.00	£3,526.93	£1,112,500.00	£81,743.91
23	£48,000.00	£3,132.26	£1,112,500.00	£72,596.73
24	£60,000.00	£3,477.20	£1,112,500.00	£64,473.11
25	£48,000.00	£2,470.48	£1,112,500.00	£57,258.54
26	£48,000.00	£2,194.03	£1,112,500.00	£50,851.28
27	£60,000.00	£2,435.65	£1,112,500.00	£45,160.99
28	£48,000.00	£1,730.48	£1,112,500.00	£40,107.45
29	£48,000.00	£1,536.84	£1,112,500.00	£35,619.41
30		£0.00	£1,112,500.00	£31,633.58
1	£48,000.00	£42,628.77	£1,112,500.00	£988,010.66
Total		£525,970.00		£8,578,304.94
		NPV	£6,432,664.95	

Table E.2: Climate change alternative

Cost						Lifecycle cost				Benefits	
Items.	**Description**	**Unit**	**Amount**	**Unit Price**	**Net Total**	**Product Lifecycle (years)**	**No. of times item requires to be replaced**	**Required amount**	**Cost of Replacement for each time**	**Descriptions**	**Net Total**
					Climate change						
1	Carbon management plan										
1.1	Carbon management strategy, (Research)	Hours	1,200	£60.00	£72,000.00	6	4	400	£24,000.00	Overall benefits due to new carbon management plan, resolving the environmental issues. (Once the railway is operational, there will be annual savings tonnes of CO2, largely due to the displacement of car journeys and replacement of diesel trains on the existing network.) Other reason is cement production is carbon intensive as the conversion of calcium carbonate to calcium oxide. Crossrail's concrete specification requires a minimum of 50 per cent cement replacement but replacement of up to as much as 72 per cent has been achieved in instances where cement performance requirements and curing time has allowed this change.	£10,000,000.00
1.2	Management of Environment Issues (Research)	Hours	600	£60.00	£36,000.00		4	150	£9,000.00		

1.3	Emissions baseline & projections, (Measurement)	Hours	200	£85.00	£17,000.00		4	50	£4,250.00	Application of advanced method of emission measurement (Aiding to measure the emissions accurately and preventing misleading information)	£1,000,000.00
1.4	Carbon emissions from energy use in buildings, (Research)	Hours	200	£60.00	£12,000.00	6	4	50	£3,000.00	Benefits in overall maintenance costs and labour costs (using advance machine and technology for carbon emission would aid in less labour and hence less maintenance)	£1,500,000.00
1.5	Carbon emissions from energy use in buildings, (Measurement)	Hours	400	£85.00	£34,000.00		4	50	£4,250.00	Saving due to reduce in global warming impacts 9reducing the energy reduction solution that affect global warming as well as CO")	£3,600,000.00
1.6	Comparison of carbon emissions with other English HEIs	Hours	100	£120.00	£12,000.00		4	50	£6,000.00		
1.7	Required Tools and Machinery	No.	1	£120,000 .00	£120,000.00	30	0	0	£0.00		
2	**Social impact of climate change**										
2.1	Impacts on Vulnerability and Equity, (Research)	Hours	600	£100.00	£60,000.00	6	4	200	£20,000.00		
2.2	Impacts on Economic Activities and Service, (Research)	Hours	600	£100.00	£60,000.00	6	4	200	£20,000.00		

2.3	Required Tools and Machinery for social impact of climate change research	No.	1	£20,000.00	£20,000.00	30	0	0	£0.00		
2.4	Labour cost for equipment instalment	Hours	350	£90.00	£31,500.00	6	4	70	£6,300.00		
3	**Physical impacts of climate change**										
3.1	Global warming, (Research)	Hours	500	£60.00	£30,000.00	6	4	100	£6,000		
3.2	Effects on weather, (Research)	Hours	500	£60.00	£30,000.00	6	4	100	£6,000		
3.3	labour	Hours	9,000	£55.00	£495,000.00	1	29	500	£27,500.00		
Total					**£1,029,500.00**					**Total**	**£16,100,000.00**

Table E.2.1: Climate change alternative- discount rate 7.3%

Year	Cost	PV (C_i)= $\frac{1}{(1+r_t)^t}C_{it}$	Benefit	PV (B_i)= $\frac{1}{(1+r_t)^t}B_{it}$
0	£1,029,500.00			
1	£27,500.00	£25,629.08	£536,666.67	£500,155.33
2	£27,500.00	£23,885.44	£536,666.67	£466,127.98
3	£27,500.00	£22,260.43	£536,666.67	£434,415.64
4	£27,500.00	£20,745.97	£536,666.67	£404,860.80
5	£27,500.00	£19,334.55	£536,666.67	£377,316.69
6	£136,300.00	£89,309.47	£536,666.67	£351,646.49
7	£27,500.00	£16,793.25	£536,666.67	£327,722.73
8	£27,500.00	£15,650.74	£536,666.67	£305,426.59
9	£27,500.00	£14,585.97	£536,666.67	£284,647.34
10	£27,500.00	£13,593.63	£536,666.67	£265,281.77
11	£27,500.00	£12,668.81	£536,666.67	£247,233.71
12	£136,300.00	£58,519.31	£536,666.67	£230,413.52
13	£27,500.00	£11,003.64	£536,666.67	£214,737.67
14	£27,500.00	£10,255.02	£536,666.67	£200,128.30
15	£27,500.00	£9,557.34	£536,666.67	£186,512.86
16	£27,500.00	£8,907.12	£536,666.67	£173,823.73
17	£27,500.00	£8,301.13	£536,666.67	£161,997.89
18	£136,300.00	£38,344.30	£536,666.67	£150,976.59
19	£27,500.00	£7,210.05	£536,666.67	£140,705.12
20	£27,500.00	£6,719.52	£536,666.67	£131,132.45
21	£27,500.00	£6,262.37	£536,666.67	£122,211.05
22	£27,500.00	£5,836.32	£536,666.67	£113,896.59
23	£27,500.00	£5,439.25	£536,666.67	£106,147.80
24	£136,300.00	£25,124.80	£536,666.67	£98,926.19
25	£27,500.00	£4,724.32	£536,666.67	£92,195.89
26	£27,500.00	£4,402.91	£536,666.67	£85,923.48
27	£27,500.00	£4,103.37	£536,666.67	£80,077.80
28	£27,500.00	£3,824.20	£536,666.67	£74,629.82
29	£27,500.00	£3,564.03	£536,666.67	£69,552.49
30		£0.00	£536,666.67	£64,820.59
Total		£496,556.31		£6,463,644.92
		NPV	£4,937,588.61	

Table E.2.2: Climate change alternative- discount rate 8%

Year	Cost	PV (C_i)= $\frac{1}{(1+r_t)^t} C_{it}$	Benefit	PV (B_i)= $\frac{1}{(1+r_t)^t} B_{it}$
0	£1,029,500.00			
1	£27,500.00	£25,462.96	£536,666.67	£496,913.58
2	£27,500.00	23576.81756	£536,666.67	£460,105.17
3	£27,500.00	21830.38663	£536,666.67	£426,023.30
4	£27,500.00	20213.32095	£536,666.67	£394,466.02
5	£27,500.00	18716.03792	£536,666.67	£365,246.32
6	£136,300.00	85892.12014	£536,666.67	£338,191.03
7	£27,500.00	16045.98587	£536,666.67	£313,139.85
8	£27,500.00	14857.39432	£536,666.67	£289,944.30
9	£27,500.00	13756.8466	£536,666.67	£268,466.95
10	£27,500.00	12737.82092	£536,666.67	£248,580.51
11	£27,500.00	11794.27863	£536,666.67	£230,167.13
12	£136,300.00	54126.6053	£536,666.67	£213,117.72
13	£27,500.00	10111.69293	£536,666.67	£197,331.22
14	£27,500.00	9362.678637	£536,666.67	£182,714.09
15	£27,500.00	8669.146887	£536,666.67	£169,179.71
16	£27,500.00	8026.987858	£536,666.67	£156,647.88
17	£27,500.00	7432.396165	£536,666.67	£145,044.34
18	£136,300.00	34108.94267	£536,666.67	£134,300.31
19	£27,500.00	6372.08176	£536,666.67	£124,352.14
20	£27,500.00	5900.075704	£536,666.67	£115,140.87
21	£27,500.00	5463.033059	£536,666.67	£106,611.92
22	£27,500.00	5058.363943	£536,666.67	£98,714.74
23	£27,500.00	4683.670318	£536,666.67	£91,402.54
24	£136,300.00	21494.41967	£536,666.67	£84,631.98
25	£27,500.00	4015.492385	£536,666.67	£78,362.94
26	£27,500.00	3718.048505	£536,666.67	£72,558.28
27	£27,500.00	3442.637504	£536,666.67	£67,183.59
28	£27,500.00	3187.627319	£536,666.67	£62,207.03
29	£27,500.00	2951.506777	£536,666.67	£57,599.10
30		£0.00	£536,666.67	£53,332.50
Total		£463,009.38		£6,041,677.06
		NPV	£4,549,167.68	

Table E.2.3: Climate change alternative-discount rate 12.6%

Year	Cost	PV (C_i)= $\frac{1}{(1+r_t)^t} C_{it}$	Benefit	PV (B_i)= $\frac{1}{(1+r_t)^t} B_{it}$
0	£1,029,500.00			
1	£27,500.00	£24,422.74	£536,666.67	£476,613.38
2	£27,500.00	£21,689.82	£536,666.67	£423,280.09
3	£27,500.00	£19,262.72	£536,666.67	£375,914.82
4	£27,500.00	£17,107.21	£536,666.67	£333,849.75
5	£27,500.00	£15,192.90	£536,666.67	£296,491.79
6	£136,300.00	£66,875.26	£536,666.67	£263,314.20
7	£27,500.00	£11,982.96	£536,666.67	£233,849.20
8	£27,500.00	£10,642.06	£536,666.67	£207,681.35
9	£27,500.00	£9,451.20	£536,666.67	£184,441.70
10	£27,500.00	£8,393.61	£536,666.67	£163,802.57
11	£27,500.00	£7,454.36	£536,666.67	£145,472.98
12	£136,300.00	£32,812.19	£536,666.67	£129,194.47
13	£27,500.00	£5,879.41	£536,666.67	£114,737.54
14	£27,500.00	£5,221.50	£536,666.67	£101,898.35
15	£27,500.00	£4,637.21	£536,666.67	£90,495.87
16	£27,500.00	£4,118.30	£536,666.67	£80,369.33
17	£27,500.00	£3,657.46	£536,666.67	£71,375.96
18	£136,300.00	£16,099.22	£536,666.67	£63,388.95
19	£27,500.00	£2,884.72	£536,666.67	£56,295.70
20	£27,500.00	£2,561.92	£536,666.67	£49,996.18
21	£27,500.00	£2,275.24	£536,666.67	£44,401.58
22	£27,500.00	£2,020.64	£536,666.67	£39,433.02
23	£27,500.00	£1,794.53	£536,666.67	£35,020.44
24	£136,300.00	£7,899.04	£536,666.67	£31,101.64
25	£27,500.00	£1,415.38	£536,666.67	£27,621.35
26	£27,500.00	£1,257.00	£536,666.67	£24,530.50
27	£27,500.00	£1,116.34	£536,666.67	£21,785.53
28	£27,500.00	£991.42	£536,666.67	£19,347.72
29	£27,500.00	£880.48	£536,666.67	£17,182.70
30		£0.00	£536,666.67	£15,259.94
Total		£309,996.82		£4,138,148.60
		NPV	£2,798,651.79	

Table E.3: Transportation alternative improvement

Cost						Lifecycle cost				Benefit	
Items	**Description**	**Unit**	**Amount**	**Unit Price**	**Net Total**	**Product Lifecycle (years)**	**No. of times item requires to be replaced**	**Required amount**	**Cost of Replacement for each time**	**Description**	**Net Total**
Transportation											
1.1	Infrastructure improvement and design	Hours	1,200	£65.00	£78,000.00	30	0	0	£0.00	Overall Benefits due to improvement in public transport infrastructure (more people travelling by the use of station as well selling more tickets daily along with benefits of reducing the traffic above ground)	£30,000,000.00
1.2	Signalling Design and improvement, (Study)	Hours	1,000	£60.00	£60,000.00		0	0	£0.00	Overall Benefits due to improvement in Freight transportation network (replacing the transportation by another means such as waterways reduce not only the co2 but also improves the traffic)	£25,000,000.00
1.3	Landscape Design	Hours	700	£65.00	£45,500.00		0	0	£0.00	Overall Benefits due to improvement low emission	£25,000,000.00

1.4	Material and equipment for Infrastructure improvement and design		1	£150,000.00	£150,000.0 0	30	0	0	£0.00	vehicles and private cars infrastructure (using low emission vehicles underground would help to reduce the generated Co2 as well as maintaining a healthy environment, avoiding sickness and health issues for staff and people)	
1.5	Material and equipment for Landscape Design		1	£50,000.00	£50,000.00		0	0	£0.00		
1.6	Material and equipment for signalling Design and improvement		1	£50,000.00	£50,000.00		0	0	£0.00		
2	Pedestrian design and facilities										
2.1	Infrastructure design for pedestrian walkway	Hours	400	£100.00	£40,000.00	30	0	0	£0.00		
2.2	Material and equipment for pedestrian walkway		1	£75,000.00	£75,000.00		0	0	£0.00		
2.3	Labour cost for equipment for pedestrian walkway	Hours	600	£65.00	£39,000.00		0	0	£0.00		
3	Cycle design and facilities										
3.1	Infrastructure Design	Hours	400	£100.00	£40,000.00	30	0	0	£0.00		

3.2	Material and equipment for Cycles way and facilities		1	£20,000.00	£20,000.00		0	0	£0.00		
3.3	Labour cost for equipment for Cycles way and facilities	Hours	200	£85.00	£17,000.00		0	0	£0.00		
4	Waterways								£0.00		
4.1	Design Waterway and drainage	Hours	100	£85.00	£8,500.00	30	0	0	£0.00		
4.2	Material and equipment for Waterway and drainage	Hours	100	£86.00	£8,600.00		0	0	£0.00		
4.3	Labour cost for equipment for Waterway and drainage	Hours	101	£87.00	£8,787.00		0	0	£0.00		
5	Freight traffic										
5.1	Freight traffic management plan, (Assessment, research)	Hours	200	£85.00	£17,000.00	30	0	0	£0.00		
5.2	Freight traffic design	Hours	200	£85.00	£17,000.00		0	0	£0.00		
6	Low emission vehicles										
6.1	Infrastructure improvement for electric public transport		1	£1,000,000.00	£1,000,000.00	10	3	3	£3,000,000.00		

6.2	Electric public bus	No.	50	£45,000.00	£2,250,000.00		3	60	£2,700,000.00		
6.3	Material, Machinery and equipment for Electric buses		1	£300,000.00	£300,000.00		3	3	£900,000.00		
7	Private vehicle use (Low emission)	No.	300	£30,000.00	£9,000,000.00	10	3	75	£2,250,000.00		
8	Labour	Hours	1,000	£55.00	£55,000.00	1	29	700	£38,500.00		
Total					**£13,274,387.00**					**Total**	**£80,000,000.00**

Table E.3.1: Transportation alternative- Discount rate 7.3%

Year	Cost	PV (C$_i$)= $\frac{1}{(1+r_t)^t}C_{it}$	Benefit	PV (B$_i$)= $\frac{1}{(1+r_t)^t}B_{it}$
0	£13,274,387.00			
1	£38,500.00	£35,880.71	£2,666,666.67	£2,485,243.86
2	£38,500.00	£33,439.62	£2,666,666.67	£2,316,163.90
3	£38,500.00	£31,164.60	£2,666,666.67	£2,158,587.05
4	£38,500.00	£29,044.36	£2,666,666.67	£2,011,730.70
5	£38,500.00	£27,068.37	£2,666,666.67	£1,874,865.52
6	£38,500.00	£25,226.81	£2,666,666.67	£1,747,311.76
7	£38,500.00	£23,510.54	£2,666,666.67	£1,628,435.94
8	£38,500.00	£21,911.04	£2,666,666.67	£1,517,647.66
9	£38,500.00	£20,420.35	£2,666,666.67	£1,414,396.70
10	£8,850,000.00	£4,374,677.59	£2,666,666.67	£1,318,170.27
11	£38,500.00	£17,736.33	£2,666,666.67	£1,228,490.47
12	£38,500.00	£16,529.67	£2,666,666.67	£1,144,911.90
13	£38,500.00	£15,405.09	£2,666,666.67	£1,067,019.48
14	£38,500.00	£14,357.03	£2,666,666.67	£994,426.35
15	£38,500.00	£13,380.27	£2,666,666.67	£926,772.00
16	£38,500.00	£12,469.96	£2,666,666.67	£863,720.41
17	£38,500.00	£11,621.59	£2,666,666.67	£804,958.44
18	£38,500.00	£10,830.93	£2,666,666.67	£750,194.26
19	£38,500.00	£10,094.06	£2,666,666.67	£699,155.88
20	£8,850,000.00	£2,162,463.73	£2,666,666.67	£651,589.82
21	£38,500.00	£8,767.31	£2,666,666.67	£607,259.85
22	£38,500.00	£8,170.84	£2,666,666.67	£565,945.81
23	£38,500.00	£7,614.95	£2,666,666.67	£527,442.51
24	£38,500.00	£7,096.88	£2,666,666.67	£491,558.72
25	£38,500.00	£6,614.05	£2,666,666.67	£458,116.24
26	£38,500.00	£6,164.08	£2,666,666.67	£426,948.96
27	£38,500.00	£5,744.71	£2,666,666.67	£397,902.11
28	£38,500.00	£5,353.88	£2,666,666.67	£370,831.41
29	£38,500.00	£4,989.64	£2,666,666.67	£345,602.44
30	£38,500.00	£1,094.74	£2,666,666.67	£322,089.88
Total		£6,968,843.73		£32,117,490.29
		NPV	£11,874,259.56	

Table E.3.2:Tranportation alternative- Discount rate 8%

Year	**Cost**	**PV (C_i)= $\frac{1}{(1+r_t)^t}C_{it}$**	**Benefit**	**PV (B_i)= $\frac{1}{(1+r_t)^t}B_{it}$**
0	£13,274,387.00			
1	£38,500.00	£35,648.15	£2,666,666.67	£2,469,135.80
2	£38,500.00	£33,007.54	£2,666,666.67	£2,286,236.85
3	£38,500.00	£30,562.54	£2,666,666.67	£2,116,885.98
4	£38,500.00	£28,298.65	£2,666,666.67	£1,960,079.61
5	£38,500.00	£26,202.45	£2,666,666.67	£1,814,888.53
6	£38,500.00	£24,261.53	£2,666,666.67	£1,680,452.34
7	£38,500.00	£22,464.38	£2,666,666.67	£1,555,974.39
8	£38,500.00	£20,800.35	£2,666,666.67	£1,440,717.03
9	£38,500.00	£19,259.59	£2,666,666.67	£1,333,997.25
10	£8,850,000.00	£4,099,262.37	£2,666,666.67	£1,235,182.63
11	£38,500.00	£16,511.99	£2,666,666.67	£1,143,687.62
12	£38,500.00	£15,288.88	£2,666,666.67	£1,058,970.02
13	£38,500.00	£14,156.37	£2,666,666.67	£980,527.80
14	£38,500.00	£13,107.75	£2,666,666.67	£907,896.11
15	£38,500.00	£12,136.81	£2,666,666.67	£840,644.55
16	£38,500.00	£11,237.78	£2,666,666.67	£778,374.58
17	£38,500.00	£10,405.35	£2,666,666.67	£720,717.20
18	£38,500.00	£9,634.59	£2,666,666.67	£667,330.74
19	£38,500.00	£8,920.91	£2,666,666.67	£617,898.84
20	£8,850,000.00	£1,898,751.64	£2,666,666.67	£572,128.55
21	£38,500.00	£7,648.25	£2,666,666.67	£529,748.66
22	£38,500.00	£7,081.71	£2,666,666.67	£490,508.02
23	£38,500.00	£6,557.14	£2,666,666.67	£454,174.09
24	£38,500.00	£6,071.42	£2,666,666.67	£420,531.57
25	£38,500.00	£5,621.69	£2,666,666.67	£389,381.08
26	£38,500.00	£5,205.27	£2,666,666.67	£360,538.04
27	£38,500.00	£4,819.69	£2,666,666.67	£333,831.52
28	£38,500.00	£4,462.68	£2,666,666.67	£309,103.26
29	£38,500.00	£4,132.11	£2,666,666.67	£286,206.72
30	£38,500.00	£3,826.03	£2,666,666.67	£265,006.22
Total		£6,405,345.61		£30,020,755.58
		NPV	£10,341,022.97	

Table E.3.3: Transportation alternative-Discount rate 12.6%

Year	Cost	PV (C_i)= $\frac{1}{(1+r_t)^t}C_{it}$	Benefit	PV (B_i)= $\frac{1}{(1+r_t)^t}B_{it}$
0	£13,274,387.00			
1	£38,500.00	£34,191.8295	£2,666,666.67	£2,368,265.25
2	£38,500.00	£30,365.7455	£2,666,666.67	£2,103,255.10
3	£38,500.00	£26,967.8024	£2,666,666.67	£1,867,899.74
4	£38,500.00	£23,950.0910	£2,666,666.67	£1,658,880.76
5	£38,500.00	£21,270.0630	£2,666,666.67	£1,473,251.12
6	£38,500.00	£18,889.9316	£2,666,666.67	£1,308,393.53
7	£38,500.00	£16,776.1382	£2,666,666.67	£1,161,983.60
8	£38,500.00	£14,898.8794	£2,666,666.67	£1,031,957.02
9	£38,500.00	£13,231.6869	£2,666,666.67	£916,480.48
10	£8,850,000.00	£2,701,216.3237	£2,666,666.67	£813,925.82
11	£38,500.00	£10,436.1049	£2,666,666.67	£722,847.09
12	£38,500.00	£9,268.2992	£2,666,666.67	£641,960.11
13	£38,500.00	£8,231.1715	£2,666,666.67	£570,124.44
14	£38,500.00	£7,310.0991	£2,666,666.67	£506,327.21
15	£38,500.00	£6,492.0951	£2,666,666.67	£449,668.92
16	£38,500.00	£5,765.6262	£2,666,666.67	£399,350.73
17	£38,500.00	£5,120.4495	£2,666,666.67	£354,663.17
18	£38,500.00	£4,547.4685	£2,666,666.67	£314,976.17
19	£38,500.00	£4,038.6044	£2,666,666.67	£279,730.17
20	£8,850,000.00	£824,471.1444	£2,666,666.67	£248,428.22
21	£38,500.00	£3,185.3307	£2,666,666.67	£220,628.97
22	£38,500.00	£2,828.8905	£2,666,666.67	£195,940.47
23	£38,500.00	£2,512.3362	£2,666,666.67	£174,014.63
24	£38,500.00	£2,231.2044	£2,666,666.67	£154,542.30
25	£38,500.00	£1,981.5314	£2,666,666.67	£137,248.93
26	£38,500.00	£1,759.7970	£2,666,666.67	£121,890.70
27	£38,500.00	£1,562.8748	£2,666,666.67	£108,251.07
28	£38,500.00	£1,387.9883	£2,666,666.67	£96,137.72
29	£38,500.00	£1,232.6716	£2,666,666.67	£85,379.85
30	£38,500.00	£1,094.7350	£2,666,666.67	£75,825.80
Total		£3,807,216.91		£20,562,229.08
		NPV	£3,480,625.16	

Table E.4: Governance and reporting alternative

Cost						Lifecycle cost				Benefit	
Items.	**Description**	**Unit**	**Amount**	**Unit Price**	**Net Total**	**Product Lifecycle (years)**	**No. of times item requires to be replaced**	**Amount**	**Cost of replacement for each time**	**Description**	**Net Total**
Governance and reporting											
1.1	Programme/project plan assessment	Hours	2,000	£130.00	£260,000.00	10	2	700	£91,000.00	Benefits due to application of advanced project plan	£10,000,000.00
1.2	Delivery at key milestones. (assessment)	Hours	400	£100.00	£40,000.00	1	29	100	£10,000.00	Benefits due to application of advanced risk management plan (having a risk management plan will prevent the probable accidents on site during construction and operation. Also a safer design meaning that for example risks with respect to the surrounding area has been identified and planned for)	£10,000,000.00
1.3	Assessment of changes on scheme	Hours	500	£100.00	£50,000.00	1	29	100	£10,000.00		
2	**Risk management/ H&S Assessment**										
2.1	General risks	Hours	300	£110.00	£33,000.00	1	29	150	£16,500.00		

	assessment										
2.2	Design risks assessment	Hours	600	£90.00	£54,000.00	1	29	50	£4,500.00		
2.3	Financial risks assessment	Hours	500	£90.00	£45,000.00	1	29	50	£4,500.00		
2.4	Health and safety assessment	Hours	500	£90.00	£45,000.00	1	29	50	£4,500.00		
Total					**£527,000.00**					**Total**	**£20,000,000.00**

Table E.4.1: Governance and reporting alternative- Discount rate 7.3%

Year	Cost	PV (C_i)= $\frac{1}{(1+r_t)^t}C_{it}$	Benefit	PV (C_i)= $\frac{1}{(1+r_t)^t}B_{it}$
0	£527,000.00			
1	£50,000.00	£46,598.32	£666,666.67	£621,310.97
2	£50,000.00	£43,428.07	£666,666.67	£579,040.97
3	£50,000.00	£40,473.51	£666,666.67	£539,646.76
4	£50,000.00	£37,719.95	£666,666.67	£502,932.68
5	£50,000.00	£35,153.73	£666,666.67	£468,716.38
6	£50,000.00	£32,762.10	£666,666.67	£436,827.94
7	£50,000.00	£30,533.17	£666,666.67	£407,108.98
8.00	£50,000.00	£28,455.89	£666,666.67	£379,411.91
9.00	£50,000.00	£26,519.94	£666,666.67	£353,599.18
10	£141,000.00	£69,698.25	£666,666.67	£329,542.57
11	£50,000.00	£23,034.20	£666,666.67	£307,122.62
12	£50,000.00	£21,467.10	£666,666.67	£286,227.97
13	£50,000.00	£20,006.62	£666,666.67	£266,754.87
14	£50,000.00	£18,645.49	£666,666.67	£248,606.59
15	£50,000.00	£17,376.97	£666,666.67	£231,693.00
16	£50,000.00	£16,194.76	£666,666.67	£215,930.10
17	£50,000.00	£15,092.97	£666,666.67	£201,239.61
18	£50,000.00	£14,066.14	£666,666.67	£187,548.56
19	£50,000.00	£13,109.17	£666,666.67	£174,788.97
20	£141,000.00	£34,452.81	£666,666.67	£162,897.46
21	£50,000.00	£11,386.12	£666,666.67	£151,814.96
22	£50,000.00	£10,611.48	£666,666.67	£141,486.45
23	£50,000.00	£9,889.55	£666,666.67	£131,860.63
24	£50,000.00	£9,216.73	£666,666.67	£122,889.68
25	£50,000.00	£8,589.68	£666,666.67	£114,529.06
26	£50,000.00	£8,005.29	£666,666.67	£106,737.24
27	£50,000.00	£7,460.66	£666,666.67	£99,475.53
28	£50,000.00	£6,953.09	£666,666.67	£92,707.85
29	£50,000.00	£6,480.05	£666,666.67	£86,400.61
30			£666,666.67	£80,522.47
Total		£663,381.82		£7,948,850.10
	NPV	£6,758,468.28		

Table E.4.2: Governance and reporting alternative- discount rate 8%

Year	Cost	PV (C_i)= $\frac{1}{(1+r_t)^t}C_{it}$	Benefit	PV (C_i)= $\frac{1}{(1+r_t)^t}B_{it}$
0	£527,000.00			
1	£50,000.00	£46,296.30	£666,666.67	£617,283.95
2	£50,000.00	£42,866.94	£666,666.67	£571,559.21
3	£50,000.00	£39,691.61	£666,666.67	£529,221.49
4	£50,000.00	£36,751.49	£666,666.67	£490,019.90
5	£50,000.00	£34,029.16	£666,666.67	£453,722.13
6	£50,000.00	£31,508.48	£666,666.67	£420,113.08
7	£50,000.00	£29,174.52	£666,666.67	£388,993.60
8	£50,000.00	£27,013.44	£666,666.67	£360,179.26
9	£50,000.00	£25,012.45	£666,666.67	£333,499.31
10	£141,000.00	£65,310.28	£666,666.67	£308,795.66
11	£50,000.00	£21,444.14	£666,666.67	£285,921.91
12	£50,000.00	£19,855.69	£666,666.67	£264,742.51
13	£50,000.00	£18,384.90	£666,666.67	£245,131.95
14	£50,000.00	£17,023.05	£666,666.67	£226,974.03
15	£50,000.00	£15,762.09	£666,666.67	£210,161.14
16	£50,000.00	£14,594.52	£666,666.67	£194,593.65
17	£50,000.00	£13,513.45	£666,666.67	£180,179.30
18	£50,000.00	£12,512.45	£666,666.67	£166,832.69
19	£50,000.00	£11,585.60	£666,666.67	£154,474.71
20	£141,000.00	£30,251.30	£666,666.67	£143,032.14
21	£50,000.00	£9,932.79	£666,666.67	£132,437.17
22	£50,000.00	£9,197.03	£666,666.67	£122,627.00
23	£50,000.00	£8,515.76	£666,666.67	£113,543.52
24	£50,000.00	£7,884.97	£666,666.67	£105,132.89
25	£50,000.00	£7,300.90	£666,666.67	£97,345.27
26	£50,000.00	£6,760.09	£666,666.67	£90,134.51
27	£50,000.00	£6,259.34	£666,666.67	£83,457.88
28	£50,000.00	£5,795.69	£666,666.67	£77,275.81
29	£50,000.00	£5,366.38	£666,666.67	£71,551.68
30			£666,666.67	£66,251.56
Total		£619,594.79		£7,505,188.90
	NPV	£6,358,594.10		

Table E.4.3: Governance and reporting-discount rate 12.6%

Year	**Cost**	**PV (C$_i$)=** $\frac{1}{(1+r_t)^t}C_{it}$	**Benefit**	**PV (B$_i$)=** $\frac{1}{(1+r_t)^t}B_{it}$
0	£527,000.00			
1	£50,000.00	£44,404.97	£666,666.67	£592,066.31
2	£50,000.00	£39,436.03	£666,666.67	£525,813.78
3	£50,000.00	£35,023.12	£666,666.67	£466,974.93
4	£50,000.00	£31,104.01	£666,666.67	£414,720.19
5	£50,000.00	£27,623.46	£666,666.67	£368,312.78
6	£50,000.00	£24,532.38	£666,666.67	£327,098.38
7	£50,000.00	£21,787.19	£666,666.67	£290,495.90
8	£50,000.00	£19,349.19	£666,666.67	£257,989.25
9	£50,000.00	£17,184.01	£666,666.67	£229,120.12
10	£141,000.00	£43,036.33	£666,666.67	£203,481.46
11	£50,000.00	£13,553.38	£666,666.67	£180,711.77
12	£50,000.00	£12,036.75	£666,666.67	£160,490.03
13	£50,000.00	£10,689.83	£666,666.67	£142,531.11
14	£50,000.00	£9,493.64	£666,666.67	£126,581.80
15	£50,000.00	£8,431.29	£666,666.67	£112,417.23
16	£50,000.00	£7,487.83	£666,666.67	£99,837.68
17	£50,000.00	£6,649.93	£666,666.67	£88,665.79
18	£50,000.00	£5,905.80	£666,666.67	£78,744.04
19	£50,000.00	£5,244.94	£666,666.67	£69,932.54
20	£141,000.00	£13,135.64	£666,666.67	£62,107.05
21	£50,000.00	£4,136.79	£666,666.67	£55,157.24
22	£50,000.00	£3,673.88	£666,666.67	£48,985.12
23	£50,000.00	£3,262.77	£666,666.67	£43,503.66
24	£50,000.00	£2,897.67	£666,666.67	£38,635.57
25	£50,000.00	£2,573.42	£666,666.67	£34,312.23
26	£50,000.00	£2,285.45	£666,666.67	£30,472.68
27	£50,000.00	£2,029.71	£666,666.67	£27,062.77
28	£50,000.00	£1,802.58	£666,666.67	£24,034.43
29	£50,000.00	£1,600.87	£666,666.67	£21,344.96
30			£666,666.67	£18,956.45
Total		£420,372.89		£5,140,557.27
	NPV	£4,193,184.38		

<u>*Table E.5: Economic effect alternative*</u>

	Cost					**Lifecycle**				**Benefit**	
Items	**Description**	**Unit**	**Amount**	**Unit Price**	**Net Total**	**Product Lifecycle (years)**	**No. of times item requires to be replaced**	**Amount**	**Cost of Replacement for each time**	**Description**	**Net Total**
Economic effect											
1.1	Providing better connections between a station and the surrounding, (Study)	Hours	150	£100.00	£15,000.0000	10	2	50	£5,000.00	Economic benefits due to improving the connections between a station and the surrounding area and adding extra train coaches and increasing the total number of journeys	£10,500,000.00
1.2	Adding extra train coaches	No.	20	£100,000.00	£2,000,000.00	30	0	0	£0.00		
1.3	Adding extra public buses in entire local network	No.	30	£40,000.00	£1,200,000.00	10	2	5	£200,000.00	Benefits due to boosting and increasing the level of overall local economy	£9,500,000.00
1.4	Overall public transport improvement (technology, design, equipment)		1	£1,500,000.00	£1,500,000.00	10	2	1	£1,500,000.00	Benefits due to improving the public transport operation in entire local network	£15,500,000.00
1.5	labour cost	hours	2,000	£55.00	£110,000.00	1	29	1000	£55,000.00		
Total					**£4,715,000.00**				**Total**		**£35,500,000.00**

Table E.5.1: Economic effect alternative- discount rate 7.3%

Year	Cost	PV (C_i)= $\frac{1}{(1+r_t)^t}C_{it}$	Benefit	PV (B_i)= $\frac{1}{(1+r_t)^t}B_{it}$
0	£4,715,000.00			
1	£55,000.00	£51,258.15	£1,183,333.33	£1,102,826.96
2	£55,000.00	£47,770.88	£1,183,333.33	£1,027,797.73
3	£55,000.00	£44,520.86	£1,183,333.33	£957,873.00
4	£55,000.00	£41,491.95	£1,183,333.33	£892,705.50
5	£55,000.00	£38,669.10	£1,183,333.33	£831,971.57
6	£55,000.00	£36,038.31	£1,183,333.33	£775,369.59
7	£55,000.00	£33,586.49	£1,183,333.33	£722,618.45
8	£55,000.00	£31,301.48	£1,183,333.33	£673,456.15
9	£55,000.00	£29,171.93	£1,183,333.33	£627,638.54
10	£1,760,000.00	£869,992.38	£1,183,333.33	£584,938.06
11	£55,000.00	£25,337.62	£1,183,333.33	£545,142.64
12	£55,000.00	£23,613.81	£1,183,333.33	£508,054.65
13	£55,000.00	£22,007.28	£1,183,333.33	£473,489.89
14	£55,000.00	£20,510.04	£1,183,333.33	£441,276.69
15	£55,000.00	£19,114.67	£1,183,333.33	£411,255.07
16	£55,000.00	£17,814.23	£1,183,333.33	£383,275.93
17	£55,000.00	£16,602.27	£1,183,333.33	£357,200.31
18	£55,000.00	£15,472.76	£1,183,333.33	£332,898.70
19	£55,000.00	£14,420.09	£1,183,333.33	£310,250.42
20	£1,760,000.00	£430,049.28	£1,183,333.33	£289,142.98
21	£55,000.00	£12,524.73	£1,183,333.33	£269,471.56
22	£55,000.00	£11,672.63	£1,183,333.33	£251,138.45
23	£55,000.00	£10,878.50	£1,183,333.33	£234,052.61
24	£55,000.00	£10,138.40	£1,183,333.33	£218,129.18
25	£55,000.00	£9,448.65	£1,183,333.33	£203,289.08
26	£55,000.00	£8,805.82	£1,183,333.33	£189,458.60
27	£55,000.00	£8,206.73	£1,183,333.33	£176,569.06
28	£55,000.00	£7,648.40	£1,183,333.33	£164,556.44
29	£55,000.00	£7,128.05	£1,183,333.33	£153,361.08
30			£1,183,333.33	£142,927.38
Total		£1,915,195.49		£14,252,136.32
		NPV	£7,621,940.82	

Table E.5.2:Economic effect alternative-discount rate 8%

Year	Cost	PV (C_i)= $\frac{1}{(1+r_t)^t}C_{it}$	Benefit	PV (B_i)= $\frac{1}{(1+r_t)^t}B_{it}$
0	£4,715,000.00			
1	£55,000.00	£50,925.93	£1,183,333.33	£1,095,679.01
2	£55,000.00	£47,153.64	£1,183,333.33	£1,014,517.60
3	£55,000.00	£43,660.77	£1,183,333.33	£939,368.15
4	£55,000.00	£40,426.64	£1,183,333.33	£869,785.33
5	£55,000.00	£37,432.08	£1,183,333.33	£805,356.78
6	£55,000.00	£34,659.33	£1,183,333.33	£745,700.73
7	£55,000.00	£32,091.97	£1,183,333.33	£690,463.63
8	£55,000.00	£29,714.79	£1,183,333.33	£639,318.18
9	£55,000.00	£27,513.69	£1,183,333.33	£591,961.28
10	£1,760,000.00	£815,220.54	£1,183,333.33	£548,112.29
11	£55,000.00	£23,588.56	£1,183,333.33	£507,511.38
12	£55,000.00	£21,841.26	£1,183,333.33	£469,917.95
13	£55,000.00	£20,223.39	£1,183,333.33	£435,109.21
14	£55,000.00	£18,725.36	£1,183,333.33	£402,878.90
15	£55,000.00	£17,338.29	£1,183,333.33	£373,036.02
16	£55,000.00	£16,053.98	£1,183,333.33	£345,403.72
17	£55,000.00	£14,864.79	£1,183,333.33	£319,818.26
18	£55,000.00	£13,763.70	£1,183,333.33	£296,128.02
19	£55,000.00	£12,744.16	£1,183,333.33	£274,192.61
20	£1,760,000.00	£377,604.85	£1,183,333.33	£253,882.05
21	£55,000.00	£10,926.07	£1,183,333.33	£235,075.97
22	£55,000.00	£10,116.73	£1,183,333.33	£217,662.93
23	£55,000.00	£9,367.34	£1,183,333.33	£201,539.75
24	£55,000.00	£8,673.46	£1,183,333.33	£186,610.88
25	£55,000.00	£8,030.98	£1,183,333.33	£172,787.85
26	£55,000.00	£7,436.10	£1,183,333.33	£159,988.75
27	£55,000.00	£6,885.28	£1,183,333.33	£148,137.74
28	£55,000.00	£6,375.25	£1,183,333.33	£137,164.57
29	£55,000.00	£5,903.01	£1,183,333.33	£127,004.23
30			£1,183,333.33	£117,596.51
Total		£1,769,261.92		£13,321,710.29
		NPV	£6,837,448.37	

Table E.5.3:Economic effect alternative- discount rate 12.6%

Year	Cost	PV (C_i)= $\frac{1}{(1+ r_t)^t}C_{it}$	Benefit	PV benefit
0	£4,715,000.00			
1	£55,000.00	£48,845.47	£1,183,333.33	£1,050,917.70
2	£55,000.00	£43,379.64	£1,183,333.33	£933,319.45
3	£55,000.00	£38,525.43	£1,183,333.33	£828,880.51
4	£55,000.00	£34,214.42	£1,183,333.33	£736,128.34
5	£55,000.00	£30,385.80	£1,183,333.33	£653,755.18
6	£55,000.00	£26,985.62	£1,183,333.33	£580,599.63
7	£55,000.00	£23,965.91	£1,183,333.33	£515,630.22
8	£55,000.00	£21,284.11	£1,183,333.33	£457,930.93
9	£55,000.00	£18,902.41	£1,183,333.33	£406,688.21
10	£1,760,000.00	£537,191.04	£1,183,333.33	£361,179.58
11	£55,000.00	£14,908.72	£1,183,333.33	£320,763.40
12	£55,000.00	£13,240.43	£1,183,333.33	£284,869.80
13	£55,000.00	£11,758.82	£1,183,333.33	£252,992.72
14	£55,000.00	£10,443.00	£1,183,333.33	£224,682.70
15	£55,000.00	£9,274.42	£1,183,333.33	£199,540.58
16	£55,000.00	£8,236.61	£1,183,333.33	£177,211.89
17	£55,000.00	£7,314.93	£1,183,333.33	£157,381.78
18	£55,000.00	£6,496.38	£1,183,333.33	£139,770.68
19	£55,000.00	£5,769.43	£1,183,333.33	£124,130.26
20	£1,760,000.00	£163,962.62	£1,183,333.33	£110,240.02
21	£55,000.00	£4,550.47	£1,183,333.33	£97,904.10
22	£55,000.00	£4,041.27	£1,183,333.33	£86,948.58
23	£55,000.00	£3,589.05	£1,183,333.33	£77,218.99
24	£55,000.00	£3,187.43	£1,183,333.33	£68,578.14
25	£55,000.00	£2,830.76	£1,183,333.33	£60,904.21
26	£55,000.00	£2,514.00	£1,183,333.33	£54,089.00
27	£55,000.00	£2,232.68	£1,183,333.33	£48,036.41
28	£55,000.00	£1,982.84	£1,183,333.33	£42,661.11
29	£55,000.00	£1,760.96	£1,183,333.33	£37,887.31
30			£1,183,333.33	£33,647.70
Sum		£1,101,774.68		£9,124,489.15
		NPV	£3,307,714.47	

Table E.6: Employment and skills alternative

Cost						Lifecycle cost				Benefit	
Items	**Description**	**Unit**	**Amount**	**Unit Price**	**Net Total**	**Product Lifecycle (years)**	**No. of times item requires to be replaced**	**Amount**	**Cost of Replacement for each time**	**Description**	**Net Total**
Employment and skills											
1.1	Providing adequate on job training for the staff	Hours	2,000	£70.00	£140,000.00	3	9	2000	£140,000.00	Benefits of training and development for employees due to increase the productivity of employee (assumed 30% increase)	£100,000.00
1.2	Providing adequate insurance for staff		1	£12,000.00	£12,000.00	3	9	1	£12,000.00	Benefits of providing adequate insurance for employees, reduction in overall loss	£2,000,000.00
1.3	Providing adequate insurance for equipment		1	£35,000.00	£35,000.00	3	9	1	£35,000.00	Benefits due to less incidents or zero incidents at work	£3,000,000.00
1.4	events for universities and schools		100	£100.00	£10,000.00	1	29	100	£10,000.00	Overall benefits due to reduction in personal injury compensation and benefits claims	£1,000,000.00
1.5	Joining career fairs		100	£120.00	£12,000.00	1	29	100	£12,000.00		
Total					**£209,000.00**					**Total**	**£6,100,000.00**

Table E.6.1: Employment and skills alternative- discount rate 7.3%

Year	Cost	PV (C_i)= $\frac{1}{(1+r_t)^t}C_{it}$	Benefit	PV (B_i)= $\frac{1}{(1+r_t)^t}B_{it}$
0	£209,000.00			
1	£22,000.00	£20,503.26	£203,333.33	£189,499.84
2	£22,000.00	£19,108.35	£203,333.33	£176,607.50
3	£209,000.00	£169,179.26	£203,333.33	£164,592.26
4	£22,000.00	£16,596.78	£203,333.33	£153,394.47
5	£22,000.00	£15,467.64	£203,333.33	£142,958.50
6	£209,000.00	£136,945.56	£203,333.33	£133,232.52
7	£22,000.00	£13,434.60	£203,333.33	£124,168.24
8	£22,000.00	£12,520.59	£203,333.33	£115,720.63
9	£209,000.00	£110,853.34	£203,333.33	£107,847.75
10	£22,000.00	£10,874.90	£203,333.33	£100,510.48
11	£22,000.00	£10,135.05	£203,333.33	£93,672.40
12	£209,000.00	£89,732.47	£203,333.33	£87,299.53
13	£22,000.00	£8,802.91	£203,333.33	£81,360.24
14	£22,000.00	£8,204.02	£203,333.33	£75,825.01
15	£209,000.00	£72,635.76	£203,333.33	£70,666.36
16	£22,000.00	£7,125.69	£203,333.33	£65,858.68
17	£22,000.00	£6,640.91	£203,333.33	£61,378.08
18	£209,000.00	£58,796.48	£203,333.33	£57,202.31
19	£22,000.00	£5,768.04	£203,333.33	£53,310.64
20	£22,000.00	£5,375.62	£203,333.33	£49,683.72
21	£209,000.00	£47,593.99	£203,333.33	£46,303.56
22	£22,000.00	£4,669.05	£203,333.33	£43,153.37
23	£22,000.00	£4,351.40	£203,333.33	£40,217.49
24	£209,000.00	£38,525.91	£203,333.33	£37,481.35
25	£22,000.00	£3,779.46	£203,333.33	£34,931.36
26	£22,000.00	£3,522.33	£203,333.33	£32,554.86
27	£209,000.00	£31,185.58	£203,333.33	£30,340.04
28	£22,000.00	£3,059.36	£203,333.33	£28,275.90
29	£22,000.00	£2,851.22	£203,333.33	£26,352.19
30			£203,333.33	£24,559.35
Total		£938,239.52		£2,448,958.63
		NPV	£1,301,719.12	

Table E.6.2: Employment and skills alternative- discount rate 8%

Year	Cost	PV (C_i)= $\frac{1}{(1+r_t)^t}C_{it}$	Benefit	PV (B_i)= $\frac{1}{(1+r_t)^t}B_{it}$
0	£209,000.00			
1	£22,000.00	£20,370.37	£203,333.33	£188,271.60
2	£22,000.00	£18,861.45	£203,333.33	£174,325.56
3	£209,000.00	£165,910.94	£203,333.33	£161,412.56
4	£22,000.00	£16,170.66	£203,333.33	£149,456.07
5	£22,000.00	£14,972.83	£203,333.33	£138,385.25
6	£209,000.00	£131,705.45	£203,333.33	£128,134.49
7	£22,000.00	£12,836.79	£203,333.33	£118,643.05
8	£22,000.00	£11,885.92	£203,333.33	£109,854.67
9	£209,000.00	£104,552.03	£203,333.33	£101,717.29
10	£22,000.00	£10,190.26	£203,333.33	£94,182.68
11	£22,000.00	£9,435.42	£203,333.33	£87,206.18
12	£209,000.00	£82,996.78	£203,333.33	£80,746.46
13	£22,000.00	£8,089.35	£203,333.33	£74,765.24
14	£22,000.00	£7,490.14	£203,333.33	£69,227.08
15	£209,000.00	£65,885.52	£203,333.33	£64,099.15
16	£22,000.00	£6,421.59	£203,333.33	£59,351.06
17	£22,000.00	£5,945.92	£203,333.33	£54,954.69
18	£209,000.00	£52,302.05	£203,333.33	£50,883.97
19	£22,000.00	£5,097.67	£203,333.33	£47,114.79
20	£22,000.00	£4,720.06	£203,333.33	£43,624.80
21	£209,000.00	£41,519.05	£203,333.33	£40,393.34
22	£22,000.00	£4,046.69	£203,333.33	£37,401.24
23	£22,000.00	£3,746.94	£203,333.33	£34,630.77
24	£209,000.00	£32,959.16	£203,333.33	£32,065.53
25	£22,000.00	£3,212.39	£203,333.33	£29,690.31
26	£22,000.00	£2,974.44	£203,333.33	£27,491.03
27	£209,000.00	£26,164.05	£203,333.33	£25,454.65
28	£22,000.00	£2,550.10	£203,333.33	£23,569.12
29	£22,000.00	£2,361.21	£203,333.33	£21,823.26
30			£203,333.33	£20,206.72
Total		£875,375.21		£2,289,082.61
		NPV	£1,204,707.40	

Table E.6.3: Employment and skills alternative- discount rate 12.6%

Year	Cost	PV (C_i)= $\frac{1}{(1+r_t)^t} C_{it}$	Benefit	PV (B_i)= $\frac{1}{(1+r_t)^t} B_{it}$
0				
1	£22,000.00	£19,538.19	£203,333.33	£180,580.22
2	£22,000.00	£17,351.85	£203,333.33	£160,373.20
3	£209,000.00	£146,396.64	£203,333.33	£142,427.35
4	£22,000.00	£13,685.77	£203,333.33	£126,489.66
5	£22,000.00	£12,154.32	£203,333.33	£112,335.40
6	£209,000.00	£102,545.34	£203,333.33	£99,765.01
7	£22,000.00	£9,586.36	£203,333.33	£88,601.25
8	£22,000.00	£8,513.65	£203,333.33	£78,686.72
9	£209,000.00	£71,829.16	£203,333.33	£69,881.64
10	£22,000.00	£6,714.89	£203,333.33	£62,061.84
11	£22,000.00	£5,963.49	£203,333.33	£55,117.09
12	£209,000.00	£50,313.62	£203,333.33	£48,949.46
13	£22,000.00	£4,703.53	£203,333.33	£43,471.99
14	£22,000.00	£4,177.20	£203,333.33	£38,607.45
15	£209,000.00	£35,242.80	£203,333.33	£34,287.26
16	£22,000.00	£3,294.64	£203,333.33	£30,450.49
17	£22,000.00	£2,925.97	£203,333.33	£27,043.07
18	£209,000.00	£24,686.26	£203,333.33	£24,016.93
19	£22,000.00	£2,307.77	£203,333.33	£21,329.43
20	£22,000.00	£2,049.53	£203,333.33	£18,942.65
21	£209,000.00	£17,291.80	£203,333.33	£16,822.96
22	£22,000.00	£1,616.51	£203,333.33	£14,940.46
23	£22,000.00	£1,435.62	£203,333.33	£13,268.62
24	£209,000.00	£12,112.25	£203,333.33	£11,783.85
25	£22,000.00	£1,132.30	£203,333.33	£10,465.23
26	£22,000.00	£1,005.60	£203,333.33	£9,294.17
27	£209,000.00	£8,484.18	£203,333.33	£8,254.14
28	£22,000.00	£793.14	£203,333.33	£7,330.50
29	£22,000.00	£704.38	£203,333.33	£6,510.21
30			£203,333.33	£5,781.72
Total		£588,556.77		£1,567,869.97
		NPV	£770,313.20	