A Web-Based Decision Support System (DSS) for Preliminary Risk Assessment of Brownfield Sites

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DECLARATION

This thesis has not been submitted in substance for any other degree or award at any university or place of learning, nor is being submitted concurrently in candidature for any other degree or other awards. I confirm that the work's intellectual content results from my own independent work/investigation and efforts and no other person.

Charfeldine Mahammedi

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ABSTRACT

Reusing brownfield sites always raises concern for the health and safety of site workers involved in site renovations and redevelopments and, subsequently, for the residents or occupants of the sites. As a minimum, a preliminary risk assessment is necessary to determine whether a brownfield site is contaminated and, if so, ensure any redevelopment is safe and suitable for its intended use. For instance, a developer may decide to redevelop brownfield site based on a preliminary risk assessment alone without any further investigation and detailed quantitative risk assessment, provided the developer is confident that any hazards present can be addressed using appropriate measures, and the acquisition brings broad commercial benefits. Despite growing interest in the progression of risk assessment tools, there are limited instruments available to brownfield site assessors to consult when conducting investigations at the preliminary risk assessment stage. This research seeks to bridge this gap and provide a Decision Support System (DSS) PRAofBS (Preliminary Risk Assessment of Brownfield sites) Tool to assist investigators and different stakeholders by identifying potential hazards associated with brownfield sites at the preliminary stage. As a result, a clear and comprehensive conceptual framework was developed to guide research in this field and shape the DSS Tool development. Experts validated the framework through a questionnaire survey. While the validation of the DSS Tool was facilitated by two approaches, firstly the DSS was uploaded to the internet, which involved testing tool by experts in terms of a graphical user interface (GUI), level of information, quality of data. The second approach was carried out by functional testing, which involved testing the tool's outputs against real–life case studies to confirm information agreement. The framework validation results can be divided into two parts. Firstly, the statistical analyses revealed that the top information to identify the source of hazards is site history, made ground, invasive species, previous mining, storage of materials and old tanks, presence of radon, underground services and buildings and other structures. Furthermore, site geology, site hydrology, site hydrogeology, and site topography were rated as top information to identify the contaminants' pathway movement. At the same time, future site use scenario is critical to identify the critical receptor of the population most likely to be exposed and/or susceptible to soil contamination. Secondly, the likelihood of potential hazards was calculated by using a Voting Analytic Hierarchy Process (VAHP), which was useful for prioritizing and generally distinguishing potential hazards from more likely to least likely threats. On the subject of DSS validation, most of the participants reported that they found DSS easy to use. They were also positive about the level and quality of information and knowledge provided by the decision support system. In particular, they found it to be helpful for the preliminary risk assessment process of brownfield site. Finally, it is anticipated that, with some modifications, the DSS Tool could become a commercially viable interface.

Keywords: Brownfield Sites, Contaminated sites, Site investigation, Preliminary risk assessment, Conceptual framework, Decision–making, VAHP, Statistical analysis, Hazard, Risk assessment. Pollutant linkage model, Decision Support System (DSS).

LIST OF PUBLICATIONS

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UNDER PREPARATION

C. Mahammedi; L. Mahdjoubi; C.A. Booth; Butt,T. E. A Web–based Decision Support System (DSS) for Preliminary Risk Assessment of Brownfield Sites.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
BIM	Building Information Modelling
BSI	British Standards Institute
CLARINET	Contaminated Land Rehabilitation Network for Environmental Technologies in Europe
CSS	Cascading Style Sheet
DCLG	Department for Communities and Local Government
DEFRA	Department for Environment, Food, and Rural Affairs
DoE	Department of the Environment
DSS	Decision Support System
GUI	Graphical User Interface
HTML	Hypertext Mark-up Language
MCDM	Multi-Criteria Decision–Making
Part 2A	Part 2A of the Environmental Protection Act 1990
PDL	Previously Developed Land (the abbreviation is used under the context of the UK regulations and policies in this thesis)
PHP	Hypertext Pre-Processor
SPSS	Statistical Package for the Social Sciences
USEPA	United States Environmental Protection Agency
VAHP	Voting Analytic Hierarchy Process
DAO	Data Access Object

1. CHAPTER 1: INTRODUCTION

1.1 Background of the Study

Constraints on the use of green spaces for development purposes has meant brownfield sites have become increasingly popular for redevelopment in recent years, especially in places where demand for residential and commercial property is high (De-Sousa, 2000; Gray, 2019). The reuse of brownfield lands has been a significant policy objective in England since the late 1990s (Schulze Bäing and Wong, 2012), aimed at reducing urban sprawl and minimising greenfield development, as well as contributing to a more compact form of urban development. The UK government is committed to prioritising the development of brownfield sites. This supports the United Nations SDG (sustainable development goal) 11 'Indicators for Sustainable Cities and Communities', which requires the best information and communication technologies (Pierce, 2018). Sustainable development requires using as little previously undeveloped land for new development as possible.

In 2012, there was approximately 45,120 ha of publicly identified brownfield sites in England, including all vacant and derelict land, which could be reused (Sinnett *et al.*, 2014). However, as brownfield sites have had previous use(s), they may contain hazards that can pose potential risks, particularly to human health and the built environment (Ashton *et al.*, 2008; Swartjes, 2015). For instance, the documentary Toxic Town: The Corby Poisonings (Kennedy, 2020) narrates the story of a landmark legal battle by a group of women aiming to uncover the truth about congenital disabilities in the Northamptonshire town being caused by toxic waste from the steelworks that had not been disposed of safely. Elsewhere, the concentration of cadmium in livestock organs exceeding the acceptable limits has been observed due to the presence of lead and cadmium from a previous mining site in Morocco (Nouri and Haddioui, 2015). Likewise, in China, cadmium from a zinc smelter contaminated leaf and root vegetables particularly (Li *et al.*, 2016). Furthermore, in April 2014, a number of cases of ill health were recorded affecting some residents in the former mining area of Gorebridge, Midlothian. It was discovered that the residents were suffering from health problems related to exposure to carbon dioxide (CO2) where ancient coal mines were the main cause (BBC, 2014). All the incidents highlighted above serve as a stark reminder of the potential jeopardies involved with reusing of brownfield sites.

Charles *et al*. (2002) discuss that buildings and constructed facilities come into contact with contaminated ground often lead to a wide range of physical and chemical changes in the proprieties of the construction materials which may appear after many years of completion of construction (Charles and Skinner, 2004; Skinner, Charles and Tedd, 2005).

Prior to any redevelopment of a brownfield site, it is important to conduct a preliminary risk assessment, is together sufficient information to develop an independent professional opinion about the health and safety in terms of human health and the built environment by identifying actual or potential hazards from brownfield condition of the site (Environment Agency, 2004). However, a good preliminary site appraisal can present considerable information to identify potential or existing health and safety constraint to be designed for the brownfield site and is likely to reduce problems and conflicts later. Therefore, as more information regarding the site becomes available, the risks can be minimised. Addressing the complex parameters involved in the risk assessment process comprehensively and successfully requires expertise and knowledge from a number of disciplines, ranging from geotechnical engineers to chemists (Martin and Toll, 2006).

The successful investigation of brownfield sites typically requires multidisciplinary expertise, a multi-staged approach, and multi-agency regulation to analyse the large volume of information needed to make a full risk assessment of the site. Risk assessment is complex and requires knowledge from many disciplines, taking into account the range of contexts in which decision have to be made. These include complying with; industry standards, relevant legislative frameworks, health and safety regulations as well as, accounting for total operating costs and benefits, and addressing issues of environmental impacts, sustainability, and importantly the prevention of further and/or future contamination (Bello-Dambatta, 2010). The literature reveals challenges facing the investigators of brownfield sites to identify and assess the risks and hazards associated with brownfield site development (Rudland *et al*., 2001; Dixon *et al.*, 2007; Searl, 2012; Mahammedi *et al.*, 2020). This generally results in a rise in site development costs and an extended period of design and site works. Therefore, the correct information needed at preliminary stage to develop such a site must be collected and used in the most cost-effective manner (Martin and Toll, 2006).

1.2 Knowledge Gap

In pursuing policies to reuse and redevelop brownfield sites, different stakeholders (e.g. landowner, occupier or investor) need to be aware of brownfield land issues (Rudland *et al.,*2001). However, the uncertainty underlying risk assessment of brownfield lands can affect their judgement. The decision to redevelop a brownfield site may be influenced by the fact that the site's environmental condition is unknown, and the real possibility of unexpected hazards. Subsequently, land acquisition without appropriate investigation may result in a developer incurring a total loss of profit on a scheme. In a study reported by Laidler *et al*. (2002), a developer purchased land on which it planned to build private houses without a preliminary investigation into the background or site history. After acquisition and major delays, costs resulted when the site was found to have been the place of previous gasworks. The developer had to pay and wait for additional investigations and scheme design, which seriously affected the project profits.

The preliminary risk assessment of brownfield sites needs to be more comprehensive and adequate information should be presented for those involved with brownfield development to have a better site appraisal (Bello-Dambatta, 2010). According to the Environmental Agency (2008), the lack of information increases uncertainties in identifying and assessing hazards, which leads to poor communication between stakeholders, possibly leading to different suitably qualified stakeholders reaching to different conclusions even when presented with the same information. However, excessive detail should be avoided, and the level of detail should be no more than is needed for robust decisions to be taken.

Challenges facing the developers and other stakeholders to identify and assess the risks and hazards associated with brownfield site development leaves a significant research gap that needs to be filled. Amongst the difficulties facing brownfield site assessors is the number of potential risks on brownfield site redevelopment is far than assessors can expect to identify (Kovalick and Montgomery, 2017). For example, addressing the complex parameters involved in the risk assessment process is sometimes failed by assessors where many of application were refused by local authorities due to not comprehensively and successfully identify potential hazards. Another challenge in the assessment of brownfield sites is commonly required expertise and knowledge from a number of disciplines, ranging from geotechnical engineers to geochemical scientist to provide an independent professional report about the risks, particularly to human health and the built environment, by identifying actual or potential hazards of the site (Nathanail and Bardos, 2005; Nathanail, Bardos and Nathanail, 2011). This may increase misunderstanding and communication issues between different stakeholders.

Despite significant advances in risk assessment of brownfield sites, several limitations exist in the preliminary stage of risk assessment of brownfield sites. One of the key limitations is the uncertainties due to the inability to identify and assess potential hazards with confidence, in particular for stakeholders with limited knowledge of such sites (Searl, 2012). However, the uncertainty underlying risk assessment of brownfield sites will affect developer and other stakeholders to decide whether the site is a problem, and/or is likely to be a problem during and/or following the site's redevelopment. The uncertainties associated with the brownfield site assessment are likely to continue unless the development of comprehensive and easy tools enables the assessors to reduce their uncertainty and boost their confidence in making decisions. For example, a developer may decide to use a remediation option to bring a site up to standards higher than is strictly necessary to protect human health. This implies that "over remediation" leading to excessive costs for developers.

The absence of a central body of knowledge is among several obstructs to stakeholder's involvement in brownfield site development (Searl, 2012). In addition, preliminary risk assessments of brownfield sites can be expensive, resource-intensive, and time-consuming when examining a large number of sites at the regional or national scales (Laidler *et al*., 2002; Locatelli *et al.*, 2019). Therefore, these limitations reveal the need to take a holistic approach to develop a decision support system to assist assessors and other stakeholders identifying and prioritising potential hazards associated with brownfield sites.

1.2.1 Research Justification

The redevelopment of brownfield sites have been identified as a major element of achieving sustainable urban regeneration. However, in some cases, the redevelopment of brownfield sites have been known by a lack of long-term consideration of impacts, as well as a failure to comprehensively examine the environmental, economic and social issues, which form the basis of sustainability (Ahmad *et al.*, 2018). It is therefore, Wedding and Crawford-Brown (2007) developed and implemented an framework (**Error! Reference source not found.**) that can be used to address and monitor sustainability throughout the life cycle of brownfield. The Framework enables the use of sustainability indicators to monitor holistically the long-term sustainability of brownfield redevelopments. The life cycle of a Brownfield

Regeneration Framework can be categorised into three phases, namely: planning and design, construction and remediation, and operation. The first phase involves planning and designing brownfield, which is critical because decisions taken at this stage will affect the sustainability of development throughout its life cycle. The second phase of the life cycle includes the remediation and construction. Although brownfield sites are not necessarily contaminated, they do require at least an initial on-site investigation to confirm. The third phase in the life cycle is the operational phase, which begins with the handover of the project and ends when the site becomes deserted again. This phase includes the study of the effects related to use, management processes and long-term maintenance.

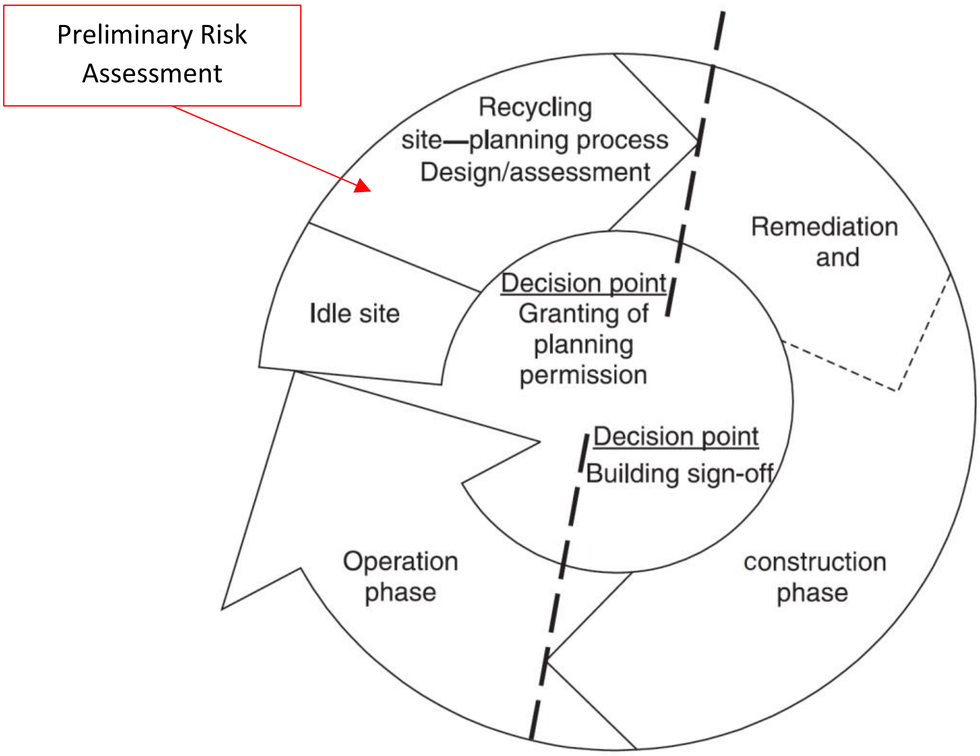

Figure 1:1 The brownfield redevelopment project land-use life cycle

Source: Wedding and Crawford-Brown (2007)used with permission from Kalliopi PEDI

A major characteristic of brownfield regeneration is that it is known by uncertainty and thus increased risk (Attoh-Okine and Gibbons, 2001). This uncertainty is usually due to a lack of environmental information and redevelopment at brownfield sites, particularly in relation to potential pollution which thereafter increases the significance of risk considerations when deciding whether and how to redevelop a site (Wylie and Sheehy, 1999). Therefore, the complexity of hazards, risk and environmental legislation surrounding the reuse of brownfield sites necessitates a preliminary risk assessment prior to their redevelopment which can be conducted in the phase 1 of brownfield regeneration life cycle (Wedding and Crawford-Brown, 2007). Most prevailing efforts have been targeted at in depth site investigations, which are often costly, time–consuming, and may not be required at the early stages of a site development. However, there is a collective absence of knowledge, methods and computer models that can present a complete framework to carry out a preliminary risk assessment that is simpler, quicker and sufficient, not only for risk assessor but also effectively communicative for a diverse range of stakeholders with or without risk assessment expertise. Therefore, this study aims to bridge this gap by designing and creating an innovative Decision Support System (DSS), by not only identifying hazards but also exposing the degree of presence.

1.3 Proposition, Aim and Objectives

1.3.1 Proposition

The main proposition of this research is that improved identifying and prioritising potential hazards associated with brownfield sites at the preliminary assessment stage could result in better decision-making regarding their redevelopment.

1.3.2 Aim and Objectives

This study aims to develop a decision support system (DSS), named PRAoBS (Preliminary Risk Assessment of Brownfield Sites), for the preliminary risk assessment of brownfield sites. It is intended that the proposed DSS will aid the identification of potential hazards and, in doing so, highlight challenges facing those stakeholders dealing with the decision-making on brownfield site redevelopments. Moreover, the DSS will enable them to promote safer redevelopment and minimise the risks to future occupants of brownfield sites and neighbouring lands.

The aim of this study will be achieved through the following stepwise set of objectives:

1. To critically review brownfield site definitions, their scope within the UK legislation context and their assessment process.
2. To conduct a critical review of the literature to identify potential hazards associated with brownfield site development.
3. Examine the state-of-the-art of existing risk assessment models and tools of brownfield sites.

4. Develop and validate the conceptual framework to guide the design of the DSS.
5. Design and test a web-based DSS, based on the outcome of the framework validation.
6. Provide conclusions, contribution to knowledge, and future recommendations.

1.4 The Research Process

Given the nature of the present study, the philosophical paradigm of this research sits on pragmatist epistemological position, located between the positivist/realist and constructivist/constructionist epistemologies, where positivist paradigm used to test and generalise the results (Gray, 2013), while an interpretivist paradigm is used to construct reality as it is conceived in various cases (Crotty, 1998). Indeed, this study takes a sceptical attitude in gaining, validating, verifying and testing knowledge. Based on the chosen philosophical position, the research processes designed to achieve the objectives of the research include: reviewing and synthesising current literature on the related fields of the research; developing a new concept to describe the area and subject of the study; empirically testing and presenting the findings in the form of new knowledge (Sarantakos, 2012).

An overview of the research is detailed in Figure *1*:*2*. This shows a six-stages process, which includes both quantitative and qualitative methods. Mixed methods are used to provide both breadth and depth in collecting, analysing and understanding the data to create the DSS tool. Stage one includes the literature review that will help in developing the research aim and objectives. Stage two involves the creation of a conceptual framework using existing literature to guide the development of the DSS tool. Stage three uses a questionnaire to validate the literature findings by experts. Stage four comprises the development of the DSS tool. Stage five uses a quantitative data analysis and case studies to complete the approval of the DSS tool. Finally, Stage six includes conclusions and recommendations for future work.

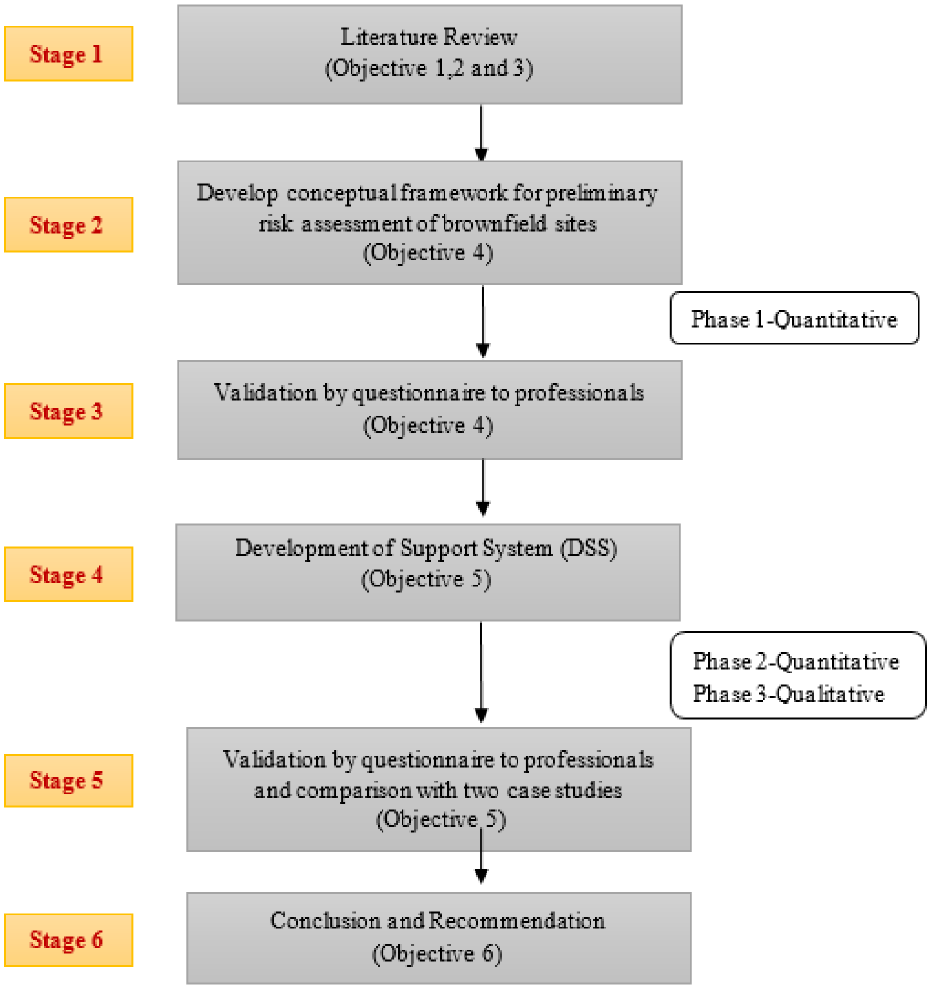

Figure 1:2 Schematic representation of the research process

1.5 Structure of the Thesis

This thesis is organised into eight chapters as shown schematically in Figure 1:3. Contents of each chapter are summarised in the following:

Chapter 1: In this chapter, the research background and knowledge gap are presented highlighting the research gaps. This chapter also presents the research aim and objectives as well as the thesis structure.

Chapter 2: This chapter is the first part of the literature review that provides a general overview of brownfield sites, its definition and scope within the legislative context of the United Kingdom and the policy drivers. The chapter also discusses the causes that lead to brownfield sites and its risk assessment process.

Chapter 3: This chapter presents an overall view of the potential hazards associated with brownfield sites. It defines three types of hazards including physical, chemical and biological hazards. The chapter also establishes the state-of-the art of the existing tools that could be appropriate for brownfield sites assessment.

Chapter 4: This chapter describes and justifies the philosophical stance, research strategies as well as the research methods of this study. The research design of this study with data collection and analysis are also presented and explained in this chapter.

Chapter 5: This chapter discusses the development of the proposed conceptual framework to conduct a preliminary risk assessment of brownfield sites based on pollutant linkage model. The key information to determine the model was identified from the literature as well as the potential hazards for each information.

Chapter 6: This chapter validates the conceptual framework developed in the previous chapter.

Chapter 7: This chapter presents the development of a Web-based Decision Support System (DSS) for Preliminary Risk Assessment of Brownfield sites (PRAoBS) based on the findings of the conceptual framework validation. The validation of the DSS adopts two approaches. Firstly, a quantitative method carried out through a structured online survey to collect data. Secondly, two case studies were performed to compare the tool outputs with the real report results.

Chapter 8: An overall summary of the research presented and discussed in this chapter. The contribution to knowledge is highlighted. The limitations of this study and suggested areas for further research are also presented in this chapter.

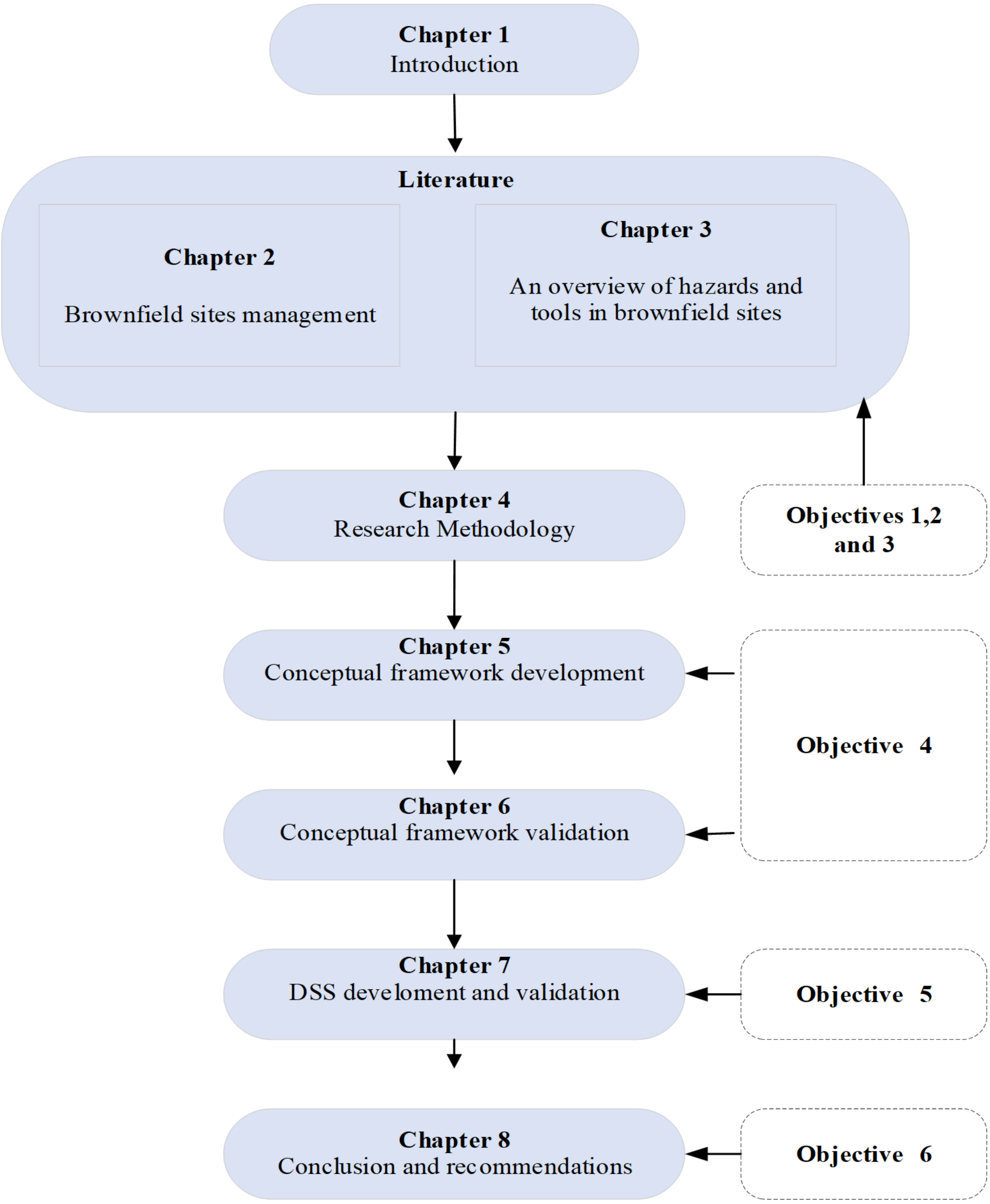

Figure 1:3 Structure of the thesis demonstrates the linkage between the thesis chapters and the thesis objectives.

2. CHAPTER 2: MANAGEMENT OF BROWNFIELD SITES

2.1 Introduction

Brownfield sites may pose a risk to a range of receptors including humans, ecosystems, water quality, property, plants, animals, etc., particularly in countries with a considerable legacy of industrial societies as a result of both past and present industrial processes, waste disposal activities and the built environment. Furthermore, such potential risks, and uncertainty relating to threats, may lead to prevent or delay the development of the sites, which may contribute to long-term dereliction and rising pressure to develop greenfield land.

This chapter deals with the management of brownfield sites, and it is divided into five main sections: Section 2.1 provides an introduction to the management of brownfield sites chapter. Section 2.2 attempts to identify the conceptual definition of brownfield site, which can be found in different states, local laws and programs, and it examines issues involved in developing an accepted definition, where it should include terms that are unambiguous and allow programs and practitioners flexibility to address brownfield as built environmental problems. Section 2.3 presents the causes that lead to brownfield sites; and Section 2.4 illustrates brownfield sites scope within the legislative context of the United Kingdom, its extent and implications, policy drivers and the brownfield site risk assessment process. Section 2.5 presents a summary of the chapter.

2.2 Brownfield Site Definition

The term "*Brownfield Site*" has become an important focus for urban policy in those countries with notable industrial histories. However, the literature indicates there is an absence of an universally agreed definition for "*Brownfield Site*", which has caused difficulties, interference and uncertainty for assessors in identifying which sites fall within this category (College of Estate Management, 1999). Alker *et al.* (2000) highlight issues caused by the absence of an agreed brownfield definition, including the confusion and misunderstanding caused by various stakeholders adopting different definitions of brownfield sites.

According to Yount (2003), a conceptual definition of brownfields should contain unambiguous terms and should allow policymakers and practitioners wide latitude in addressing the dual nature of brownfields as both environmental and economic problems. Otherwise, Alker *et al.* (2000) identified several major elements among the definitions of brownfields from governments and institutions: "derelict", "vacant", "previously developed" and "contaminated".

The term vacant is defined by Aberdeen City Council (2016) as any previously developed land, without physical constraint, which the planning authority has indicated is currently available for redevelopment. In comparison, the term "derelict land" is defined as previously developed land, which has physical constraint caused by its previous use, and it must not be ready for redevelopment without actions. Whereas the land is legally defined as 'contaminated land' where substances are causing or could cause significant harm to people, property or protected species, significant pollution of surface waters (e.g. lakes and rivers) or groundwater. Furthermore, Previously Developed Land (PDL) is the land that has been previously developed by humans (Tang, 2011).

The brownfield definition associated with dereliction or underused land seems popular among Western European countries (Oliver *et al.*, 2005). While the US definition strongly connects the brownfields with contamination, where vacant and unused land that is not suspected of contamination is not labelled as a brownfield. Therefore, the concepts of "derelict", "vacant" and "previously used" can be derived either from the results of deindustrialisation or sub–urbanisation. However, the concept of "contamination" is closely tied to industrial activities and less relevant to suburbanisation. Currently, a number of different federal, state and local definitions of brownfields are in use.

Table *2.1* summarises how these common elements have been considered in several institutions.

Table 2.1 The common Elements in Brownfield definitions (adapted from Tang, 2011)

Elements / Institutions	Derelict	Contaminated	Previously Developed	Vacant
CABERNET[1] (Europe)	✓	○	✓	✓
England NLUD[2]	✓	–	✓	✓
USEPA (2009)	✓	✓	✓	–
NRTEE[3] (CANADA)	✓	✓	✓	✓
Alker *et al.* (2000)	✓	✓	✓	✓
This study	○	✓	○	○

✓ *essential element in the definition*
○ *secondary element in the definition*
- *no mention of the element*
[1] *Millar et al. (2005)*
[2] *DCLG (2007)*
[3] *USEPA (2009)*
[4] NRTEE (2003)

In the context of this study, brownfields integrate the definition of contaminated land as an essential element in the definition, while the terms of vacant, derelict and previously developed considered as secondary elements in the definition. Consequently, a brownfield site refers to a land that may be derelict and/or vacant that could be contaminated by hazards resulting from previous usages.

2.3 The Causes of "Brownfield Sites"

Not all brownfield sites are contaminated, but many sites are, and such sites can present significant redevelopment challenges (Charles, 2005). Research conducted by (Vik and Bardos, 2003; Environment Agency, 2008; Harrison, 2015) investigated brownfields' causes and concluded that the primary source of hazards is the contamination arising from past industrial use. In addition, several authors (Leach and Goodger, 1991; Charles *et al.*, 2002;

Charles, 2005; Wilson *et al.*, 2007) have investigated hazards related to site with poor properties, where the ground is regarded as geotechnical problems. Otherwise, studies by (Leach and Goodger, 1991; Barry, 1991; Sarsby, 2000; Charles, 2005) has noted that existing buildings in previously used land may present an additional source of hazards during demolition activities. Demolition of old works without adequate decommissioning and decontamination has significant potential for the release of hazardous substances, as well as ongoing hazards through the distribution and use of contaminated demolition product (Sarsby, 2000).

The ways in which areas with a long history of activities are affected by contamination are unlimited. However, it is possible to identify three main stages as shown in Figure 2:*1*, applicable to industrial sites. These are:

- The delivery, storage and handling of raw materials
- The activities process itself
- The disposal of wastes

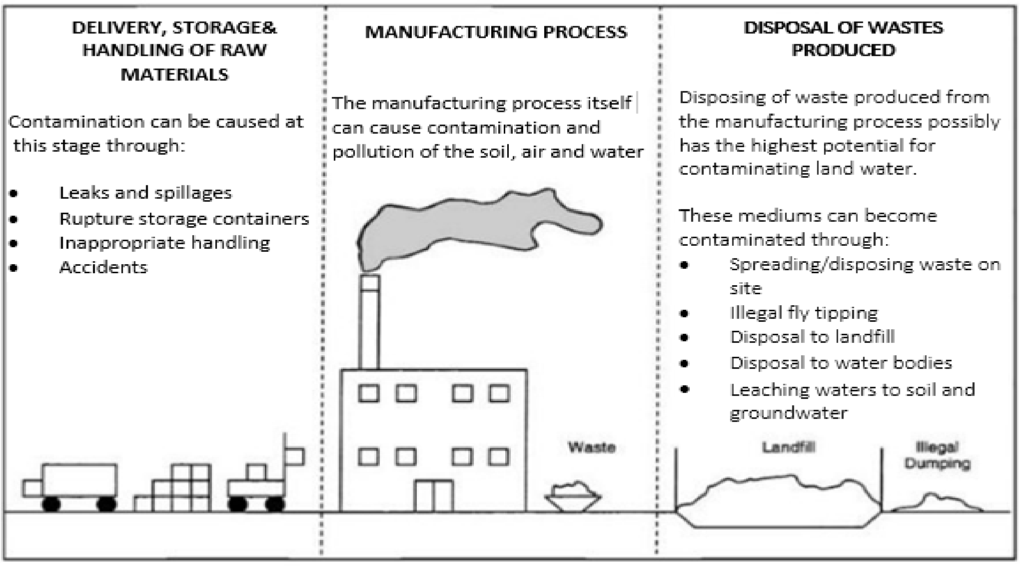

Figure 2:1 The potential for land contamination through previous activities cycle related to the release mechanism of the contaminants.

Source: Syms (2007), reused with permission from John Wiley & Sons.

Delivery, handling and storage of raw materials are diverse and may vary within industries, as well as from industry to industry and over time. Chemicals and other liquid raw materials stored in tanks and silos, all of which may leak or result in contamination through spills and leakage. However, the contaminants substances leak due to failures of the tank body, accidentally ruptured to equipment on the tank, damage to or wear–and–tear of fuel feed lines. Many studies have reported fuel storage and distribution at industry manufacture (Gossen and Velichkina, 2006; Demirel and Altin, 2017; Motta *et al.*, 2017) as one of the leading causes of soil and groundwater contamination due to leakage from piping, from underground storage tanks. In addition, leakage is not limited just for fuel and oil substances, where a number of studies (Dasuki *et al.*, 2015; Zhang *et al.*, 2015; Núñez-Delgado *et al.*, 2018; Kim *et al.*, 2019; Law *et al.*, 2019) investigate leakage of contaminants including heavy metals, organic compounds, and inorganic compounds. Meanwhile, delivery and storage facilities are responsible for pollutants to be absorbed on to soil, where contaminants could be dissolved in water and readily migrate through soil system and reaching groundwater.

Disposal of wastes may cause pollution, where liquid waste leaking from landfill is a significant issue related to ground pollution (Figure 2:*1*). Sarsby and Felton (2006) covered the causes and mechanism of leachate leakage from landfill sites. However, waste is considered 'hazardous' under environmental legislation when it contains substances or has properties that might make it harmful to human health or the environment.

In addition to the contamination hazards of waste disposal in brownfield sites (Leach and Goodger, 1991; Charles *et al.*, 2002; Wilson *et al.*, 2007) investigate hazardous gas threats generated from biodegradable wastes. Landfill sites contain biodegradable materials, during the long process of decomposition, the considerable reduction in the volume and consequent settlement of the landfill is accompanied by the generation of gas and leachate formation. Biological reactions in landfills can convert organic compounds to several different gases, called biogas(Jonidi-Jafari and Talaiekhozani, 2010). Biogas comprises approximately 60 % methane, 40 % carbon dioxide and small amounts of water vapour, hydrogen sulphide, ammonium and halogenated hydrocarbons (Ohimain and Izah, 2017).

The sources of hazards in brownfield sites are based on three main types. Firstly, contaminated sites which have left a legacy of contamination from operational activities. Secondly, landfill sites share the chemical and biological hazards with contaminated sites; meanwhile, they arise the site's inability to support the buildings due to the site's insufficient bearing capacity. Thirdly, existing buildings in brownfield sites, including industrial and commercial buildings arise hazards related to the release of chemical hazards during demolition activities.

2.4 Brownfield Policy: A UK Perspective

Over the last few decades, the UK government, urban planners, corporations and institutions have paid significantly more attention to sustainable urban development and smart growth in urban areas. One proposal that has gained widespread political support in the UK, during this time, is the redevelopment of brownfield sites, which are often located in the core sections of large urban areas and, as such, are prime candidates for urban revitalization efforts (Wedding and Crawford-Brown, 2007).

The UK is committed to developing brownfield sites as a priority. Consequently, on 4 January 2016, a £1.2bn fund was announced to prepare brownfield sites for the construction of starter homes in the next five years. This is intended to fast–track the creation of at least 30,000 new starter homes and up to 30,000 'market' homes on 500 new sites by 2020 (Perraudin, 2016). To achieve the government strategy for sustainable development in the UK, it requires using as little previously undeveloped land for new development as possible. One way to reduce urban land-use is to build as many new dwellings as possible on previously developed land (Bieback, 2017). The reuse of brownfield or previously developed land has been a major policy objective in England since the late 1990s, aimed at reducing urban sprawl and greenfield development, as well as contributing to a more compact form of urban development (Schulze Bäing and Wong, 2012). However, redevelopment of brownfield sites presents a huge hazard considering the difficulties to develop because of their constraints, including physical characteristics and contamination issues.

Greenberg *et al.* (2001) have produced extensive evidence to show the positive impact of brownfield redevelopment on ecological (air and water) and public health. For instance, concentrated development reduces energy consumption by reducing vehicle use, leading to less greenhouse gas generation. Moreover, putting more people and jobs in the concentrated city means less need for watering large lawns, fewer swimming pools, and less chance of contaminating reservoirs and underground water supplies in the protected open spaces available on many metropolitan areas. Public health may have benefited by cleaning up the brownfield sites by removing contaminated areas that can be a source of neighbourhood resident exposure because of windblown dust and illegal entrance. Otherwise, Adams *et al.* (2010) highlight the advantage of brownfield sites in countries with high industrial history regarding the growing housing shortage, where a million new homes could be built on previously used land in England, with more than 2,600 new sites identified in the 2018 (Booth, 2019).

2.4.1 Brownfield Sites Legislation

The Brownfield land policy is mainly relevant both technically and legislatively with issues of redevelopment, groundwater pollution prevention and control, waste management and industrial site decommissioning (Bello-Dambatta, 2010) and is dealt with through several legislations including :

- *The Contaminated Land Regime*: in response to increasing contamination hazards related to brownfield sites the UK Government introduced new legislation in April 2000 (Part 2A of the Environmental Protection Act 1990) requiring all local authorities to take responsibility to identify contaminated sites that pose a risk to health, buildings or the environment (Ministry of Housing, 2014). Under Part 2A, the risk assessment should also identify the potential sources, pathways and receptors (‘pollutant/ contaminant linkages’) and evaluate the risks.

- *The Planning System:* considers the “suitable for use” approach as the most adequate to deal with UK industrial legacy of contaminated sites, which take in consideration the environmental, social and economic objectives (Defra, 2012). In these conditions, all intolerable risks are determined, and that the remediation of such land enables it to be suitable for use. However, this approach can deal with brownfield sites, which also consists of the UK policy on appropriate development.

- *Building Regulations*: contain the rules for building work in new and altered buildings to make them safe and accessible and limit waste and environmental damage. In particular, Approved Document C provides instruction on resistance to contaminants and moisture, including ensuring buildings are protected from both weather and water damage, from dangerous substances such as radon and methane, and that guidelines are followed when preparing a building site and its foundations for construction (Billington, 2007b).

- *The Water Resources Act 1991:* is an Act of the Parliament of the United Kingdom that regulates water resources, water quality and pollution. Part II of the Act provides the general structure for the management of water resources.

- *The Construction (Design and Management) Regulations 2015:* Whatever your role in construction, CDM aims to improve health and safety in the industry by helping you to: sensibly plan the work, so the risks involved are managed from start to finish. have the right people for the right job at the right time.

- *The Water Resources Act 1991* is used for the prevention and removal of pollution from controlled waters. This is useful in situations where there is historic contamination, and Part IIA does not apply, for example where the contamination is contained within the relevant water body or in diffuse pollution cases where contaminant sources cannot be identified.

- The *EU Groundwater Directive:* is used to protect groundwater resources from discharges and disposals of substances. This regulation is implemented in the UK through the Groundwater Regulations 2009.

2.4.2 Regulatory Roles and Responsibilities

2.4.2.1 The role of the Local Authority

Local authorities are responsible for identifying contaminated sites that pose a risk to health, buildings, or the environment under Part 2A of the Environmental Protection Act 1990 (Ministry of Housing, 2014), and ensuring remediation occurs for designation of given sites and apportionment of liability. In addition, local authorities should have a proper understanding of the risks to make regulatory decisions and ensure that the summary of the dangers is understandable to the layperson, including the owner of land and people affected by the decisions.

2.4.2.2 The role of Local Planning Authorities (LPA)

The planning authority duty to decide whether to grant or refuse planning permission for building and development in your area. It also creates a Development Plan, which sets out its planning policies. Moreover, it ensures that the developer undertakes risk assessment of the brownfield sites to determine whether more detailed investigation is required, and implements any remedial requirements responsibly and effectively (Gateshead Council, 2013).

2.4.2.3 The role of the Health and Safety Executive (HSE)

The Health and Safety Executive (HSE) is responsible for enforcement of the Health and Safety at Work etc Act 1974, which is the primary piece of legislation designed to protect occupational health and safety in Great Britain. The HSE with local authorities is responsible for enforcing the Act and a number of other statutory instruments related to the working environment including the CDM (Construction Design and Management) 2015 Regulations (HSE, 2017). For example, they provide advice regarding buildings originally sited on brownfield land. These buildings are likely to have contained high levels of asbestos, being constructed when asbestos containing materials (ACMs) were widely used to insulate and fireproof.

2.4.2.4 The role of the Environment Agency

In England and Wales, the Environment Agency is statutory consultee required under Part 2A of the Environmental Protection Act 1990 to protect and improve the environment (Environment Agency, 2012). As such they will be consulted on applications where pollution of surface water or groundwater is involved, or where the water environment might be at risk of pollution as a result of the development (Laidler, Bryce and Wilbourn, 2002). The Environment Agency also provides scientific and technical advice on applications for development of contaminated lands and lands close to or on landfill sites and within floodplain areas.

2.4.2.5 The role of the developer

The role of developer regarding the development of brownfield land is mainly focused on identifying the constraints associated with the development of such as lands to make necessary decisions with requisite confidence. In addition, under planning act 1990 the developer is responsible for ensuring that the development is safe and determining whether the land is suitable for its proposed use (Legislation.gov.uk, 2016), or can be made so by remedial action. In order to demonstrate this, the developer is responsible to: i) determine whether the land in question can be affected by contamination through source –pathway – receptor pollutant linkages model; ii) ensure that development is safe and suitable for use for the proposed development; iii) determine what is the remediation strategy to break those linkages, deal with any unacceptable risks and enable safe development and future occupancy of the site and neighbouring land (Barclay, 2011; Manchester City Council, 2016).

2.4.2.6 The role of the Department of Environment, Food and Rural Affair (DEFRA)

DEFRA is responsible for developing and implementing legislation and all associated policy on the contaminated land, environment, food and rural issues. It is also responsible for protecting the countryside and supporting sustainable green development (DEFRA, 2010).

2.4.2.7 The role of the English Heritage

Its role is to help people understand, value, care for and enjoy England's rich historic environment. Produced by the National Heritage Act 1983, its responsibilities as mention in legislation are: To protect ancient monuments and historic buildings. Therefore, it provides advice regarding the impacts of brownfield on the historic environment, elements of cultural heritage and historic landscapes.

2.4.3 Risk-Based Approach (Pollutant Linkage Model)

The assessment and management of land contamination risks management have been adopted in many European countries based on the pollutant linkage concept (Figure 2:*2*) including a contaminant source, a pathway along which the contaminant can move to a receptor that may be affected (Vik *et al.*, 2001). These are the three fundamental components to any risk assessment in many countries (Vik and Bardos, 2003), in which this concept is used in the UK Model Procedures (CLR11) in the context of risks assessment and environmental health management of contaminated land. Each of these elements can exist independently, but with the absence of pollutant linkage, they are not able to create a risk. However, this type of relation combination of Source-Pathway-Receptor is defined as a pollutant linkage (Environment Agency, 2004). This information will enable the local planning authority to determine whether more detailed investigation is required, or whether any proposed remediation is satisfactory (Ministry of Housing, 2014).

Figure 2:2 Pollutant linkage concept (derived from Environmental Agency, 2008)

This concept is limited to contaminated sites with chemical contamination, while this research study illustrates that the term brownfield site has been widely adopted to describe previously developed land. Therefore, the pollutant linkage concept can be extended to be adopted for brownfield sites.

2.4.3.1 Source

A source is defined by Environmental Agency (2008) as any harmful or toxic substance present in the ground (as a solid, liquid or gas/vapour). Section 2.3 provides more details about the source of hazards in brownfield sites.

2.4.3.2 Pathway

A pathway can be defined in two ways: firstly, a pre-exposure route of contaminants, which investigates the parameter that may affect the contaminant fate and transport and, secondly, an exposure route or means by which a receptor can be exposed to, or affected by, a contaminant (Butt, Lockley and Oduyemi, 2008). However, the same contaminant may be linked to two or more distinct receptor types by different pathways, or various contaminants and/or pathways may affect the same receptor. Not all of the following exposure routes (Figure 2:3) are expected to be encountered at every site. A unique site-specific condition may also require additional exposure routes to be investigated (Environment Agency, 2008). Exposures to chemical and biological agents at high doses are often associated with a single, relatively simple pathway. For example, the highest intake of chemical warfare agents released to air will be through direct inhalation or eye contact. Exposures to chemical and biological agents at low doses rates are often associated with multiple, indirect, and complex pathways. Chemical warfare agents can be transferred from air to soil and then tracked into buildings or deposited onto plants and animals transferred to food (National Research Council, 1999). However, the pathway characterization process can be short-term hazard (over a period of hours or days) for example during earthmoving operation (dust and fumes), which mainly affecting site workers and occupiers of nearby property. Long-term hazards may result from persistent toxicants (such as dust from lead and other metals, coal tars and asbestos) blowing from a contaminated site for a period of months or years.

The main exposure pathways which a contaminant may reach a human are (Department of environmental conservation, 2017; Leach and Goodger, 1991):

- Direct Soil ingestion
- Dust ingestion

- Consumption of homegrown produce
- Ingestion of soil attached to homegrown
- Inhalation of dust (indoors)
- Inhalation of dust (outdoors)
- Dermal contact with soils
- Dermal contact with soils
- Dermal contact with dust (indoors)
- Inhalation of vapours (indoors)
- Inhalation of vapours (outdoors)

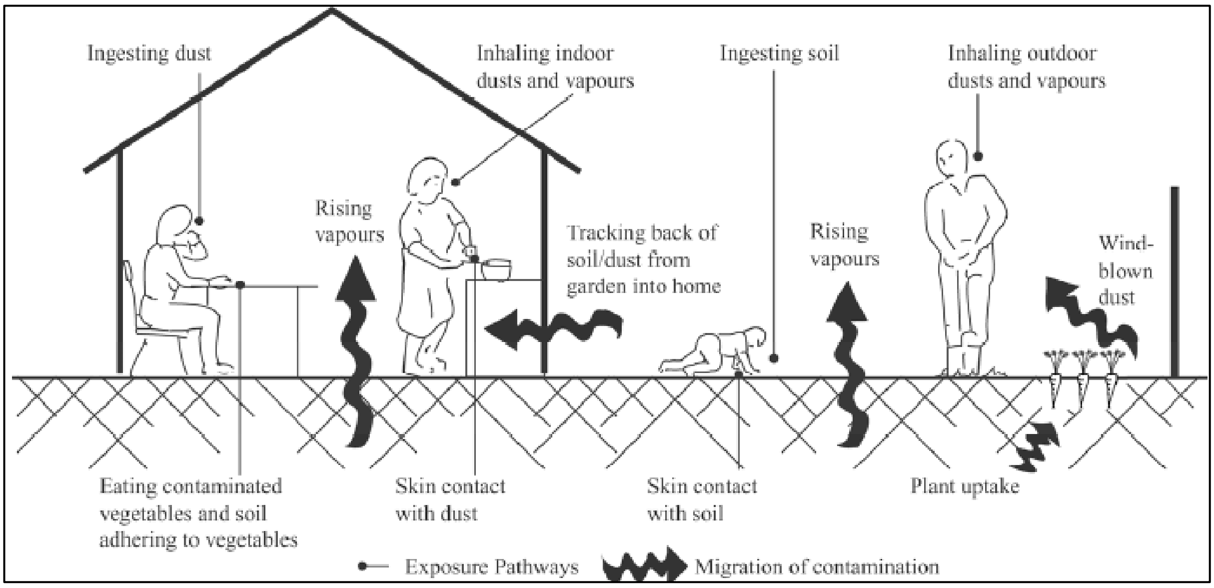

Figure 2:3 An illustration of the potential human exposure pathways

Source: Environmental Agency (2009), permission not required as it is a public domain.

2.4.3.3 Receptor

Brownfield site can contain a wide range of hazards, and there are also very different receptors for these hazards (Skinner *et al.*, 2005). According to Charles and Watts (2015), there are three interdependent systems (

Figure *2:4*), which may be at risk in brownfield redevelopments:

- The human population.
- The natural environment (e.g. surface and groundwater).
- The built environment.

Skinner *et al*. (2005) reported that physical hazards are regarded as geotechnical, and chemical and biological hazards are regarded as geoenvironmental. Physical problems may include buried foundations and settlement of filled ground (Watts and Charles, 2015). Also, chemical contamination may cause significant issues and present immediate or long–term threat to human health through soil or groundwater to plants, to amenity, to construction operations and to buildings and services. Biodegradation of organic matter may lead to the generation of gas.

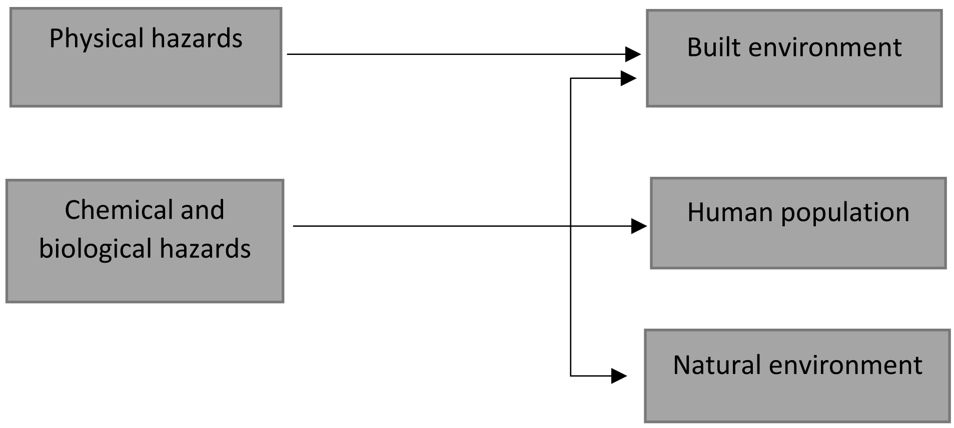

Figure 2:4 Interaction of hazards and systems at risk

Source: Skinner, Charles and Tedd (2005), reused with permission from Sharon @BRE

Risk to build environment is based on the interaction of the building and the site, it is important to estimate the risk of adverse interactions during a lifetime. When derelict sites are developed, the main emphasis is often on the hazards to the human population and the natural environment from pollution and contamination. At the same time, risks to the human population are mainly related to contaminant and other hazards such as underground services. Risks posed to human health have usually the dominant issue in the redevelopment of brownfield sites (Skinner *et al*., 2005) but, for the contaminant to pose a risk, a human receptor must be present and a reasonable pathway by which the contaminant could be transferred to the person present on the site and the occupiers could be the receptor most exposed to many of the hazards (Charles, 2005).

Risk to the natural environment is often narrowly believed to concern soil and groundwater contamination. However, several issues should be examined in the light of growing concern over degradation of the natural environment highlighted redevelopment of brownfield site may cause a disturbance, dust, and noise. It is difficult to establish an adequate balance between economic well–being and the natural environment because unlike matters of human health (Charles *et al.*, 2002).

2.4.4 Risk Assessment Process

Risk assessment is the starting point of risk management, which provides a structured framework for identifying risks and making decisions about the consequences (Rudland, Lancefield and Mayell, 2001). Risk assessment is a fundamental process in achieving effective management of the risks associated with brownfield sites.

The Environment Agency has developed a comprehensive technical framework for applying risk assessment to brownfield sites (Environment Agency, 2008). This defines a structured framework for assessment and decision making within Government's policy and legal requirements that could be adapted to apply a range of management contexts (Bello-Dambatta, 2010). The framework adopted a tiered risk-based assessment approach, where each tier of the risk assessment follows the same basics and can be divided into two main phases, as shown in **Error! Reference source not found.**.

Once identified the need for risk assessment, it will be necessary to conduct a preliminary risk assessment. However, based on the circumstances and the outcome, it may not be required to conduct an advanced risk assessment. Once the risks are assessed, and if action to eliminate or mitigate the risks is considered necessary, the next part of the process is the appraisal of options to deal with the threats, followed by implementing appropriate action (AECOM Infrastructure & Environmental UK Ltd, 2017).

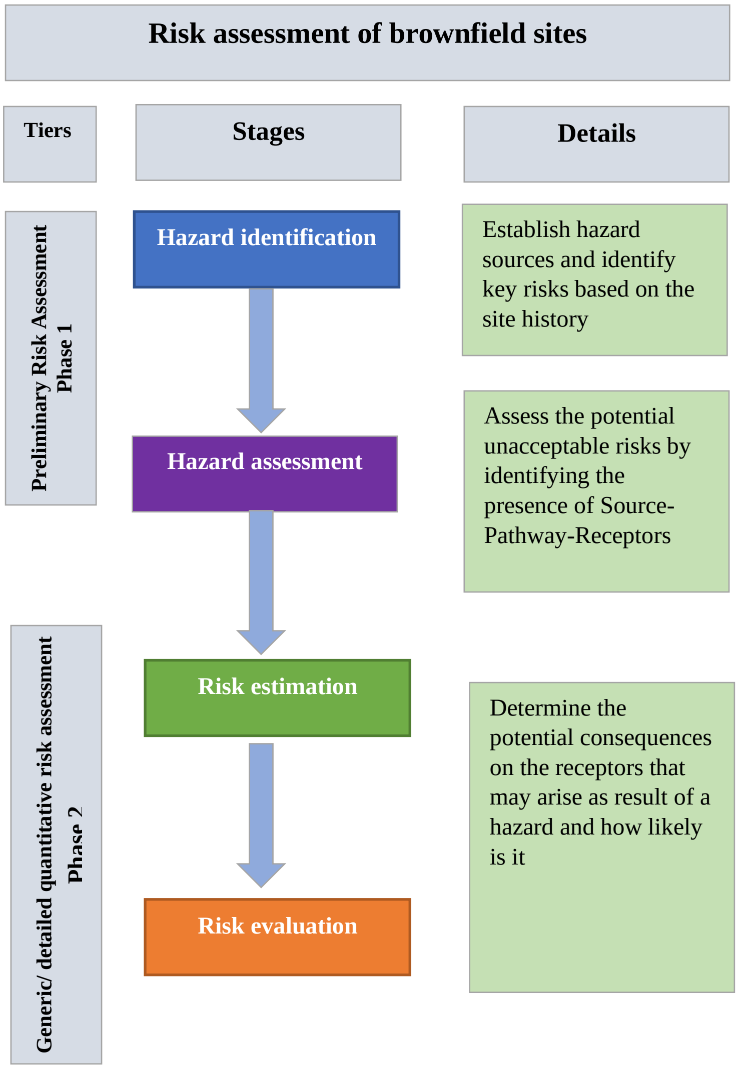

Figure 2:5 Risk assessment process of brownfield sites (derived from Environmental Agency, 2008)

2.4.4.1 Preliminary Risk Assessment (PRA)

The initial phase of brownfield site development includes preliminary risk assessment, which is a largely a desk-based information collection exercise that may consist of site reconnaissance, also known as a Desk Study (Environment Agency, 2004, 2008). This phase aims to establish whether: there are any potentially unacceptable risks on the site; further information is needed; or, the site needs to be kept under review (Environment Agency, 2016). A preliminary risk assessment analyses a wide range and volume of information to identify potential or existing constraints affecting the site to reduce problems later on in a project where the cost of dealing with those problems rapidly rises (Martin and Toll, 2006).

A successful preliminary risk assessment presents considerable information to identify potential or existing constraints to reduce problems and conflicts later. The level of details that will be necessary for site appraisal will vary depending on the scale of the proposal and the characteristics of the site. Moreover, preliminary risk assessment has become an essential component of real estate transactions, especially for commercial and industrial property. In fact, in the case of private development, understanding hazards constraints and the cost and feasibility of potential mitigation is key to understanding the true value of real property and whether a project will "pencil out" (Prasse, 2012). Table 2.2 illustrates the benefits of taking preliminary risk assessment.

Table 2.2 The benefits of conduction preliminary risk assessment of brownfield sites.

N°	Benefits of preliminary risk assessment of brownfield sites	References
1.	Identify the hazards at the early stage will prevent time delay for additional investigations.	(Laidler *et al.*, 2002)
2.	Prevent misunderstanding at later stage in the development.	(Nathanail and Bardos, 2005; NPTCBC, 2015)
3.	Avoid delays in the development stage through unexpected or accidental contamination.	(Burger *et al.*, 2006)
4.	Help developers identify and respond to any critical issues that could affect planning.	(Syms, 1999; Environment Agency, 2012)
5.	Help developers to take adequate decisions related to the acquisition of the site.	(DEFRA; Environmental Agency, 2004)
6.	Help developers to take adequate decisions related to future use of the land.	(Vik and Bardos, 2003; Syms, 2007)
7.	Help developers to take adequate decisions related to making contract for the site acquisition or development, etc.	(Syms, 2007; Agostini and Vega, 2009)
8.	Improve predictability of future issues related the development of the site.	(Kibblewhite, 2015)
9.	Improve the communication between the developer, local authorities, consultancies and clients allowing for better decision-making, which helps to improve quality and mitigate risk.	(Laidler, Bryce and Wilbourn, 2002)
10.	Fully coordinated design helps to reduce potential risk on site reconnaissance and investigation.	(Rudland, Lancefield and Mayell, 2001; Laidler, Bryce and Wilbourn, 2002)
11.	Determine the potential of hazard being present and whether future site investigation is needed.	(Department of the Environment, 1994; Nunes *et al.*, 2011; Department of environmental conservation, 2017)

12.	Determine whether any particular precaution is required during inspection or investigation.	(Department of the Environment, 1994; Sarsby, 2000; Environmental Agency, 2008)
13.	Provide information and about the legal regulation risk and/or remedial measures.	(Rudland, Lancefield and Mayell, 2001; Laidler, Bryce and Wilbourn, 2002)

2.4.4.2 Generic Quantitative Risk Assessment (GQRA)

Generic risk assessment is undertaken in which samples are collected, and contaminant concentrations are compared with generic assessment criteria (GAC) (Cheng and Nathanail, 2009). GAC values are derived using generic assumptions about sources, pathways, and receptors' characteristics and behaviour (Ja'afaru and Cheng, 2018). These values are generalized assessment criteria suitable to a wide range of soil types, site conditions and future site use scenarios. However, the Land Quality Management Ltd (LQM) and the Chartered Institute of Environmental Health have published GAC values for a wide range of pollutants that is in line with the current legal contaminated land and associated policy. The final part of this phase is consideration of the next steps, for example, if the unacceptable risk is not appropriately or sufficiently assessed, a detailed quantitative risk assessment (DQRA) is considered to generate site-specific assessment criteria.

2.4.4.3 Detailed Quantitative Risk Assessment (DQRA)

Detailed quantitative risk assessment aims to establish and use more detailed site-specific information and criteria to decide whether there are unacceptable risks (Bello-Dambatta, 2010). The site-specific assessment criteria are calculated based on toxicity data, and calculated exposure, which may include further targeted information collection to support the generation of the requirements and typically involves the use of modelling software to estimate the movement of contaminants in the media such as air and plants and the detailed exposure features of the receptor (Environment Agency, 2009c). A specialist risk assessor will almost certainly be needed to undertake the work, which should be based upon the comprehensive risk assessment guidance provided in the Model Procedures (Environment Agency, 2004)

2.5 Chapter Summary

The subject of brownfield sites has always been considered a debatable issue, due to the range of environmental, technical, financial, social issues associated with these lands. Even the simple question "What is a brownfield site?" has many diverse answers due to the absence of a universally agreeable definition. This has caused difficulties, interference and uncertainty for designers in identifying which sites fall within this category. For instance, an area including high natural levels of pollutants compounds may be considered contaminated in a general view, but most definitions relate to brownfields due to human activity, these, therefore, these may sometimes not be considered a brownfield. However, for the basis of this study, brownfield sites will integrate the definition of contaminated land as an essential element in the definition, while the terms of vacant, derelict and previously developed considered as secondary elements in the definition.

Assessment of land contamination risk management has been adopted in many European countries based on the pollutant linkage concept (Source–Pathway– Receptor), in which this concept is used in the UK Model Procedures (CLR11) in the context of risks assessment and management to health and the environment from contaminated lands. This concept is limited to contaminated sites with chemical contamination, while this research study illustrates that the term brownfield site has been widely adopted to cover the contaminated area. Therefore, the pollutant linkage concept can be readily extended to be adopted for brownfield sites.

Literature shows risk assessment of brownfield sites usually includes multi-agency regulation and multidisciplinary expertise. This requires broad integration of interdisciplinary knowledge into a coherent decision–making framework, within a current regulatory framework. In the UK the risk assessment of brownfield sites is undertaken using a tiered risk-based approach with each incremental tier involving increasing detail and complexity, involving: (i) preliminary risk assessment which is mainly an information collection exercise that may include a site reconnaissance; (ii) generic quantitative risk assessment is undertaken in which samples are collected and compared with generic assessment criteria (GAC); and (iii) detailed quantitative risk assessment which uses site-specific assessment criteria. The next chapter will review the potential hazards associated with brownfield sites and examine the state-of-the-art of tools that may be appropriate for preliminary risk assessment of brownfield sites.

3. CHAPTER 3: AN OVERVIEW OF BROWNFIELD SITE HAZARDS AND TOOLS

3.1 Introduction

From the generalisation of risk assessment of brownfield sites in the previous chapter, the process may be perceived to be quite structured and unproblematic. In fact, risk assessment of brownfield sites can be quite complex and is typically undertaken under conditions of both risk and uncertainty, often resulting from the complexity of site conditions and the hazards involved. Therefore, this chapter intends to review the hazards associated with brownfield sites and examine the state-of-the-art of existing risk assessment models and brownfield sites' tools. Section 3.2 discusses the suite of potential hazards including physical, chemical and biological threats; while, Section 3.3 presents a comprehensive review of current emerging tools that can be used to assess brownfield sites. Section 3.4 summarises the chapter.

3.2 Overview of Brownfield Sites Hazards

3.2.1 Physical Hazards

3.2.1.1 Ground Movement

High demand for land development, combined with political and commercial impetus to build on brownfield sites, means a substantial proportion of new commercial, industrial and housing developments are now built on 'fills' (Watts and Charles, 2015). Accordingly, they are built on the ground created by human activity rather than by natural geology processes. Therefore, it is crucial to know whether the site under consideration will have suitable foundation properties before construction takes place (McCormack, 2010). Besides, there must be a good understanding of fills' behaviour and the hazards associated with these lands and economically rendered appropriate development (Billington, 2007).

Charles *et al*. (2002) indicate that the foundations and superstructure of buildings can be damaged by excessive ground movements, where settlement is the most common form, but the ground may heave in certain situations. The load capacity of the ground on a brownfield site may be inappropriate as result to many causes, classified into two main types:

- The ground may have had insufficient load capacity related to the original state of the ground without the impact of human activities. This type of ground includes non–cohesive soils and highly compressible soft clay and organic soils.
- Previous human activity on the site may have created ground-related problems. Brownfield includes the hazardous of buried foundations, old pipework and tanks from previous site usage.

Studies on the engineering behaviour of brownfields (Garvin *et al.*, 1999; Charles and Skinner, 2004; Watts and Charles, 2015) have shown that in most situations the fill settlement that damages buildings has caused other than the weight of the building. This means that the ground's bearing capacity on a brownfield site may be inadequate due to a variety of factors. Settlements caused by other physical factors and chemical or biological processes need to be assessed in some cases. These findings have led several studies (Charles *et al.*, 2002; Skinner, Charles and Tedd, 2005) to describe brownfield's ground movement into the following headings: compressible fills and expansive fills. Otherwise, as the brownfield contain the concept of previous land use. Chapman, Marsh and Foster (2001) highlight the hazards of buried foundations for brownfield sites' development. Otherwise, in the last years, concerns increased to the hazards related to archaeological remains, where many projects have been delayed, and costs raised when unexpected heritage assets are encountered within a brownfield site development. Therefore, some engineering consultancies consider archaeology remains a hazard for brownfield site development.

3.2.1.1.1 Compressible Fills

Made ground or sites contain fill may present a significant issue due to the compressibility of the ground and its possibility to collapse when wet. Many brownfield sites have considerable fills, meaning that fills' behaviour supporting buildings' foundations is of increasing importance (Charles and Skinner, 2004). Otherwise, Ian and Chris (2012) reported that naturally occurring collapsing soils can be divided into two categories: firstly, those which collapse upon inundation under a total pressure equal to their overburden; and secondly when fill soils are not adequately compacted they can compress (settle) under a load of a foundation resulting in damage to the structure (Figure 3:*1*). Moreover, research conducted by Charles, Watts and BRE (1996) shows that most poorly compacted fills undergo a reduction in volume when inundated or submerged for the first time, which if it happens after building construction can cause severe damage. This phenomenon, usually termed collapse compressions, is often the most serious hazard for buildings on fill. Consequently, consideration is given not only to compression induced by an increase in applied stress but also to compression consequent on the increase in compressibility associated with an increase in moisture content (Charles and Skinner, 2004), which triggers collapse compression can be caused either by downward infiltration of surface water or by a rising groundwater level.

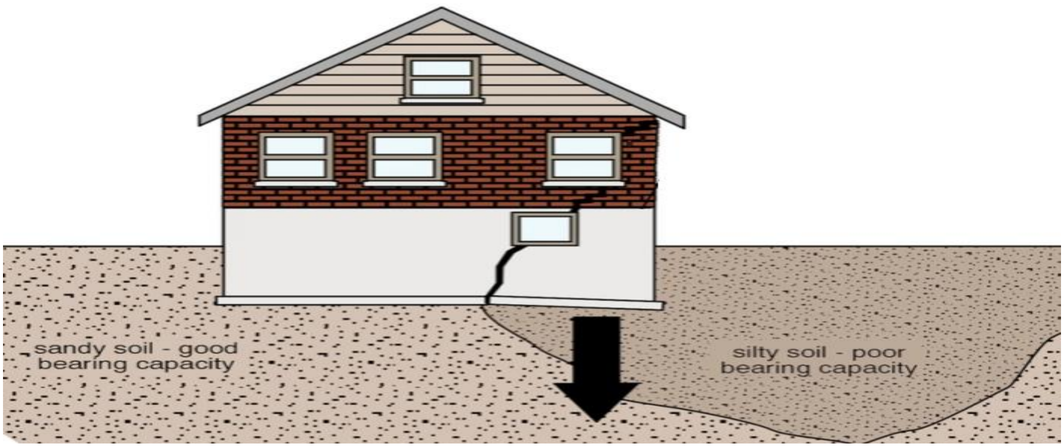

Figure 3:1 Settlement caused by insufficient bearing capacity

Source: www.carsondunlop.com, used with permission from Emily Victor @ Carsondunlop

Organic material (such as domestic rubbish/garbage) is considered amongst the most serious aspect of the diverse character of the material that may be found on fill, because it may be buried in the fill. There are other less obvious sources of organic matter. Although solid when deposited, it will deteriorate with time, and will in all probability, it will generate gaseous products of decomposition, notably methane, which is offensive and an explosion hazard (Legget, 1967). Otherwise, many industrial processes result in large quantities of waste material that must be disposed of as a fill. For example, a considerable amount of red waste is created by refining processes at aluminium works deposited in special sludge reservoirs. These and similar processes may also yield solid material that can form what appears to be acceptable solid fill. The origin of all such industrial fill must always be determined since its chemical composition may be significant (Guyer, Asce and Aei, 2013).

3.2.1.1.2 Expansion Fills

Expansive soils (i.e. soils with high clay contents) can experience significant volume variations associated with changes in their water contents (Lee D. and Ian, 2012). Therefore, it is essential to recognise that some fills, rather than settling, may expand. These may be of natural origin or human-made (i.e. clay fill), or the presence of slags from iron and steel–making processes. Fills may include clay-rich soils and rocks which contain minerals that absorb water. The more soil contains this clay, the higher its swell potential and the more water it can absorb. Therefore, the volume of the soils increases in the presence of water and shrink when they get dry, they reflect the change in volume of the ground. Shrinking can cause differential settlement while swelling pressure increases the potential of lifting or leaving of structure. For more detailed guidance, reference made to BRE Digest 298 *Low rise building foundations: the influence of trees in clay soils*, 1999. Figure 3:*2* shows the potential hazards associated with the expansion fills.

Brownfield sites filled with steel slags may also expand on wetting due to chemical reactions (Charles *et al.*, 2002). According to Garvin *et al. (*1999), the principle hazards from the presence of old blast furnace or steel is that they will expand possibly even decades after deposition, causing damage to structures and roads. There have been numerous failures documented of structures built on such slags. In 1981, BRE published the first report to highlight the potential problems of building on expansive slags.

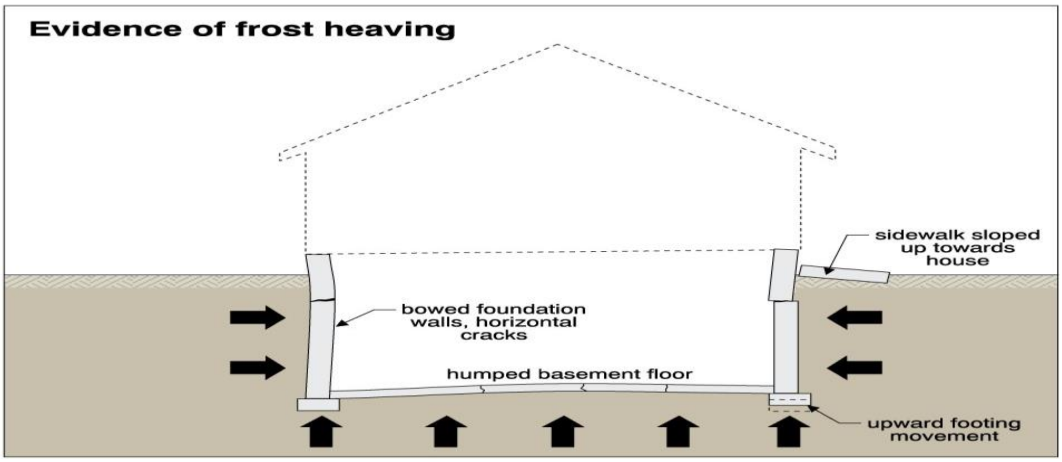

Figure 3:2 Foundation heaving due to expansive fills

Source: www.carsondunlop.com, used with permission from Emily Victor @ Carsondunlop

3.2.1.1.3 Shallow mine workings

There are a considerable number of old mine workings in the UK, many of which are unknown. Most of these are the heritage of coal mining during the 17th, 18th and 19th centuries. Other resources such as silver, lead, tin, iron, flint, limestone and refractory clays were mined at different times (Charles, 2005). Many layers of coal that were worked with during the industrial revolution now underlie urban areas. Many UK areas have experienced severe problems caused by collapsing voids (Skinner, Charles and Tedd, 2005). The collapse of old mine workings can cause sudden ground movements without warning, which can severely affect current and nearby buildings. Building houses on land which is underlain by known shallow coal workings or other mineral workings can result in substantial development costs. Brownfield sites where there is a history of mining, the presence of large voids at shallow depths should be considered (Charles *et al.*, 2002).

3.2.1.2 Obstructions. Underground services

By previous use, brownfield sites contain buildings, ancillary structures, and underground services (Figure 3:3). These pose potential barriers to redevelopment, which could be of great consequence if not anticipated and planned when discovered during construction. Also, brownfield sites cause so many problems with substances contamination because they have had buildings demolished in the past or have facilities currently requiring demolition. Several studies (Barry, 1991; Leach and Goodger, 1991; Sarsby, 2000) have noted that where structures and buildings have previously existed, these land may present additional sources of hazards during demolition activities. For instance, due to poor historical practices, it is a commonplace on some brownfield sites to discover asbestos contamination within the soil when demolition has been completed. Furthermore, some historical buildings are likely to contain high levels of contaminants, mainly as asbestos can be found in an industrial or residential building built or refurbished before the year 2000 (HSE, 2015b). Asbestos may be present in the soil as discrete fibres, or as pieces of building material; for example, abandoned industrial premises, former waste disposal sites (including those reclaimed for agricultural or amenity use etc.) and other derelict or unused land may potentially be contaminated by buried asbestos to some degree. At some sites, asbestos may also be present on the surface, e.g. on areas where it was used for heat insulation (as lagging for pipes or tanks), fire control, or in the construction of walls and roofs of the building (Forster, 2012). The critical hazards associated with building on brownfield sites are presented in Table 3.1.

Figure 3:3 Obstruction hazard example of an old oil tank found underground

Source: www.waterlineenvironmental.ca, used with permission from Waterline Environmental

Table 3.1 The key hazards associated with buildings in brownfield sites (Adapted and derived from various sources: Wallwork and Trust, 2006; Quarmby, 2011; HSE, 2015b, 2015a; Fleming, 2015)

Hazard	Risk associated	Details
Demolition	Dust	Demolition generate a lot of dust often invisible, fine, toxic mixture of hazardous materials including silica, lead and fibres that can damage the lungs, leading to diseases such as chronic obstructive pulmonary, asthma, asbestosis and silicosis.
	Noise	Repetitive, excessive noise causes long term hearing problems and can be a dangerous distraction.
	Asbestos	Demolition activities may disturb or damage materials that contain asbestos. When the fibres are released into the air and inhaled they can cause serious diseases such as mesothelioma, lung cancer, asbestosis and pleural thickening
	Vibration	Prolonged use of vibratory power tools and ground working equipment may cause a painful and debilitating industrial disease of the blood vessels, nerves and joints. In addition to long–term painful damage to worker hands and fingers – and that shocks and jolts from driving certain types of vehicles can cause serve back pain.
	Microbiological	Demolition of particular buildings like old hospital buildings exposes to a number of different microbiological hazards including pigeons (psittacosis), rats (leptospirosis) used needles (eg hepatitis B/ HIV) horsehair plaster (anthrax), sewage (tetanus)
	Synthetic mineral fibers	Synthetic mineral fibres are used largely for insulation in building walls and ceilings as well as on items such as air–conditioning ductwork.
	Polychlorinated Biphenyls (PCBS)	Workers can be exposed to PCBs when dismantling electrical capacitors and transformers or when cleaning up spills and leaks
	Falls from height	During demolition, workers can be injured falling from edges, through openings, fragile surfaces and partially demolished floors.
Poor quality	Foundation failure	The reuse of foundation may lead to different type off foundation failure including Punching shear and One–Way shear failure. These failures increase the potential of structure damage.
	Differential Settlement	The different foundation types between the old and new foundation may increaser the potential of differential settlement. In addition, different stiffness responses of similar pile types since the older piles will have been pre–loaded.

Damage to underground services can cause fatal or severe injury where underground electrical cables carry considerable hazardous because they often look like pipes, and it is hard to know if they are live just by looking at them. Injuries are usually caused by the explosive effects of connections and terminations that have been damaged but left unreported and unrepaired or deteriorated with age. Such effects can also occur when a cable is crushed severely enough to cause internal contact between the conductors (HSE, 2013a). While, the damage may occur to gas pipes when the work is carried out, or subsequently. This damage may cause leaks that lead to fire or explosion. There are two types of damage: damage that causes an immediate leak; and damage that causes a leak sometime later. Otherwise, damage to water pipes is less likely to result in injury, where leaks of water from underground pipes can affect adjacent services and reduce support for other structures (HSE, 2013a). Damage to mains pipes can result in flooding, leading to ground collapse and the possibility of environmental contamination and pollution. In some cases, such as interruption of telecommunication cables may require expensive repairs and can cause considerable damage to those relying on the system. However, the risk of personal injury to workers usually is very low (Butcher, Powell and Skinner, 2006).

3.2.2 Chemical Hazards

3.2.2.1 Key chemical contaminants associated with brownfield sites

Industrial, commercial, agriculture and landfill sites arise out common contamination hazards of the chemical nature of the hazardous substances, present in the site either by industry process, commercial activities (e.g. airport, petroleum station, etc.), fertilise agricultural lands or dangerous material deposited as fill (Nathanail, Bardos and Nathanail, 2011). The contaminated site generally refers to the site that contains elevated concentrations of potentially hazardous substances. Classification of contaminant substance are associated with specific industries or activities and are commonly found in land associated with that activity. It is estimated that between 60,000 and 90,000 chemicals are in current commercial use. Although not all of these constitute potential toxicity hazards, many will cause pollution of soils due to leakage during storage, from use in the environment or from their disposal either directly, or of wastes containing them (Harrison, 2015). As a consequence of the variety of compounds involved, many of the contamination lists have been used, and therefore, the absence of an agreed list of chemical contamination requires attention on most sites contaminated.

A review of a number of articles and reports (Barry, 1991; AECOM Infrastructure & Environmental UK Ltd, 2007) shows that different historical activities on the site might have caused different types of contamination, and the common key contaminants are presented as follows:

- Heavy metals and their compounds
- Organic compounds
- Inorganic compounds
- Radioactive

3.2.2.2 Gas emission (flammability, toxicity)

Brownfield sites can present a severe hazard to building development (Figure 3:4) because wherever biodegradable material is deposited, microbial activity will generate landfill gas (Charles *et al.*, 2002). It generally consists of methane and carbon dioxide and small quantities of volatile organic compounds (VOC) which give the gas its characteristics.

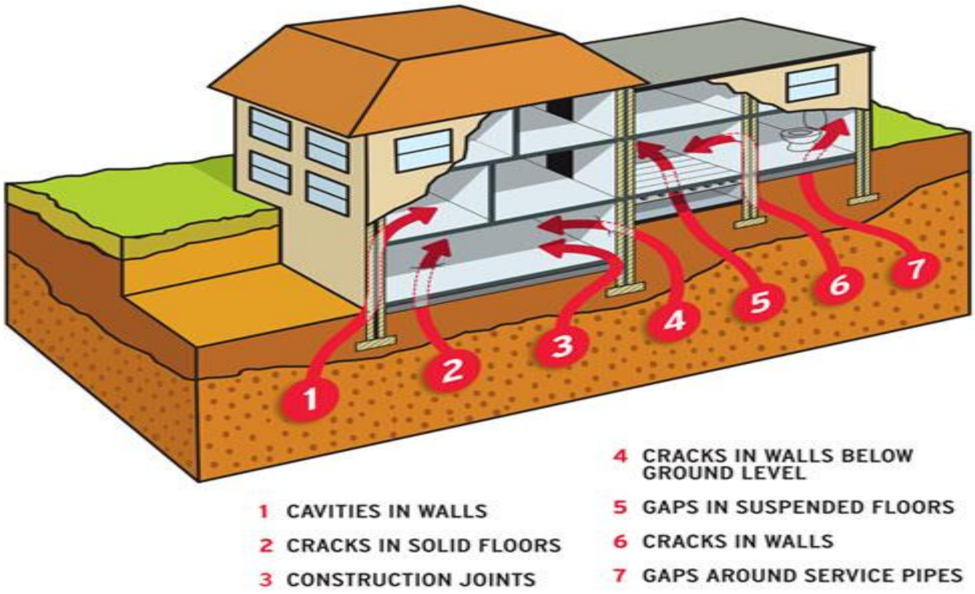

Figure 3:4 Gas entry routes into houses

Source: www.epa.gov, used with permission from Rachel Flynn @ EPA

Contamination by radon gas and its products of decay has led to concern over a long–term health of occupants of affected buildings. Radon is naturally occurring, colourless and odourless gas which is radioactive. It migrates through cracks and fissures in the subsoil until it reaches the atmosphere or enters spaces under or in buildings (Billington, 2007b). To minimize the risk of all new buildings, extensions, whether residential or non–domestic area where there may be elevated radon emissions, may need to take precautions against radon. The Health and Safety Executive (HSE) presents guidance on protection from radon in the workplace http://www.hse.gov.uk/radiation/ionising/radon.htm. Furthermore, precautions to protect buildings and occupants against random gas ingress are available from the National Radiological Protection Board NRPB and British Geological Survey (BGS). This information has been placed in the Building Research Establishment (BRE) guidance document Radon: guidance on protective measures for new dwellings (BRE Report BR 211: 3rd edition 1999).

Methane is an explosive and asphyxiating gas. Carbon dioxide, although non-flammable, is toxic. VOC are flammable and toxic and should not build up to hazardous levels in buildings (Stephenson, 2001). In addition, many of the other components of landfill gas are flammable, all are asphyxiant, and some are toxic. CIRIA (report 152) provides gas risk assessment guidelines, and the GasSIM model is also available for assessing gas emission from landfill sites. There is further discussion of gas risk assessment in the Approved Document C of the Building Regulations. Table 3.2 shows health hazards associated with gas emission in a brownfield site.

Table 3.2 Gas hazards with the risk associated (Adopted and derived from various sources: Leach and Goodger, 1991; Tracy et al., 2006; Zielinski et al., 2006; EPA, 2019)

Gas hazards	Health hazards
• Carbon monoxide • Hydrogen sulphide • Hydrogen cyanide	Toxicity
• Methane • Carbon dioxide • Hydrogen	Asphyxia, Flammable
• Lack of oxygen as result of smouldering carbonaceous. • Bacteria activities	Anoxia
• Organic vapours (e.g. benzene) • Fuel gases	Narcosis

Landfill gas can migrate significant distances, it is affected mainly by ground permeability where the presence of low permeability ground (clay, membrane, concrete slabs, etc.) may cause an increased pressure resulting in more significant migration. The accumulation of landfill gas at any level in enclosed space may cause an explosion in buildings. These have been attributed to lateral migration of landfill gas from old waste fill sites (Leach and Goodger, 1991).

3.2.2.3 Aggressive attack, and corrosion of building materials

Building materials are often subjected to aggressive environments at brownfield sites that cause physical or chemical changes. These changes may result in loss of strength or other changes that will put at risk their structure stability (Garvin *et al.*, 1999). The chemical attack on the substructure (e.g. foundations, underground services, floor slabs, basements, etc.) by aggressive ground conditions could cause movement and structural instability (Skinner, Charles and Tedd, 2005). In aggressive soils, the potential for contaminant attack depends on the following (Garvin *et al.*, 1999):

- The presence of water as a carrier of aggressive contaminants.
- The availability of the contaminant in terms of concentration, solubility and replenishment rate of the aggressive solution.
- Contact between the contaminant and the building material.
- The material's sensitivity to the contaminant, in other words, the inherent durability of the material and the properties that cause it to react or not with the contaminant.

The vulnerability of building materials and building foundation to contaminants in the soil and groundwater had attracted the attention of numerous researchers in the past (Paul, 1994; Tulliani *et al.*, 2002; Bader, 2003; Rajasekaran, 2005; Glasser, Marchand and Samson, 2008; Sotiriadis *et al.*, 2013). Therefore, the design of buildings and foundations should consider potential damage as a result of contaminants contact. In such cases, thicker building materials have the potential to reduce the contaminants attack. In addition, the choice of building location could reduce the risk of contaminants attack. For example, if site investigation shows that there is a hot spot of a particular type of contamination that will attack the building foundations then this part of the site could be contained, treated, removed or left undeveloped (Garvin *et al.*, 1999).

Mallick, Tawil and Shibani (1989) assess concrete foundations durability in a number of aggressive conditions commonly met in contaminate soil. According to the same study, environmental aggression to foundation concrete occurs due to:

- (a) Aggressive Compounds in the subsoil or groundwater surrounding the concrete,

- (b) Effect of wetting and drying.

Many deleterious processes can affect the foundations concrete and steel reinforcement before reusing foundations, it is important to ensure that the foundation materials have not deteriorated to such an extent that their required design life is impaired (**Error! Reference source not found.**). If foundation is to be reused, its materials must be sampled, and a design life reassigned which needs to be greater than that of the new building that they will support (Chapman, Marsh and Foster, 2001). Therefore, assessing the foundation's conditions before reuse depends on the details of the original materials and the exposure conditions. Further ground investigation could be needed if the initial investigation did not adequately define the exposure conditions.

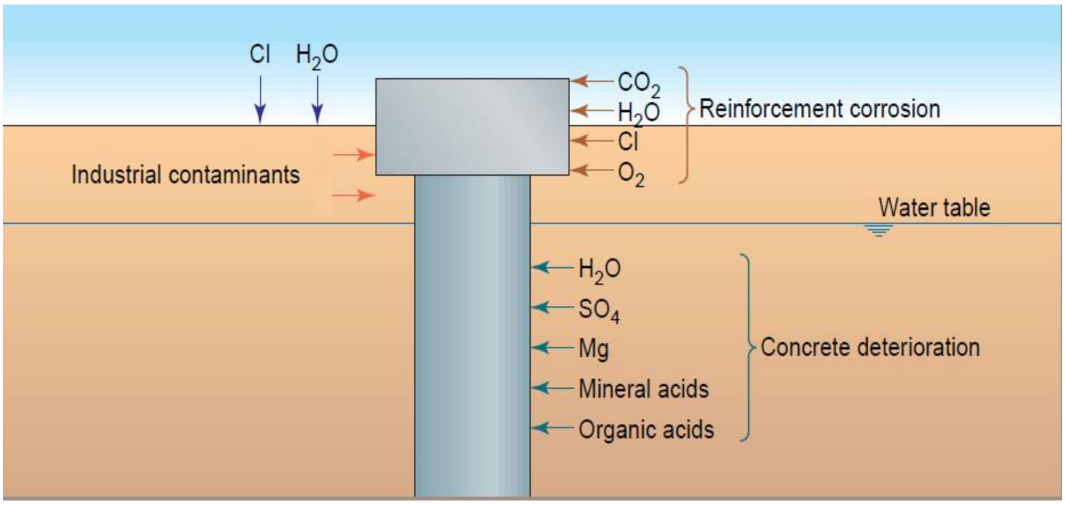

Figure 3:5 Existing foundations are constantly under attack from all directions

Source: Chapman et al. (2001), used with permission from ICE Publishing

Despite the high number of contaminants that are likely to be encountered in contaminated site, Garvin *et al*. (1999) mentioned that there is little definitive guidance on managing the risks to concrete from contaminants other than perhaps sulphate, chloride, magnesium and acids. However, only in the case of sulphate, there is an extensive remedial strategy that covers both ground concentration of sulphate and the specification of concrete.

3.2.3 Biological Hazards

3.2.3.1 Pathogenic micro-organisms

Conceptually, hospital waste, laboratory waste and cemeteries can be regarded as special kinds of landfills. Workers and residents may be infected by pathogenic micro–organisms such as bacteria and viruses that contaminate waste, which is usually formed from the decomposition of matter and results in infections (Jerie, 2016). For example, research carried out by Rodrigues and Pacheco (2010) is convinced that all cemeteries represent potential threats to human health. In the decomposition of a human body, 0.4–0.6 litres of leachate with a density of 1.23 $g \cdot cm^{-3}$ is produced per 1 kg of body weight. The leachate contains micro–organism contaminants derived from decaying bodies that may pollute substrates, surface water and groundwater, such as foot and mouth virus, *E. coli*, *campylobacter*, *salmonella*, *Leptospira* and *water born protozoa* (Rudland, Lancefield and Mayell, 2001; Chowdhury *et al.*, 2019). A study conducted by (Gwyther *et al.*, 2011) concluded that after corpse decomposition, some micro–organisms (such as anthrax spores or prions) could reside within the soil for extensive times and they may threaten water quality by leaching to groundwater and surface water. Furthermore, during the construction and maintenance of sewage and wastewater plants, workers are commonly exposed to materials that can cause disease. Sewage and wastewater contain bacteria, funguses, parasites, and viruses that can cause intestinal, lung, and other infections. Consequently, the pathogenic micro-organisms are mainly released by leachate for and work activities such as maintenance or demolition. Table 3.3 presents the micro-organisms contaminants associated with brownfields.

Table 3.3 Micro-organisms contaminants associated with brownfields

	Biological hazards				References
	Bacteria	viruses	Parasite	Fungi	
Sewages and sanitary workers	✓	✓	✓		(Curtis and Harrington, 1971; Tiwari, 2008)
Hospital wastes	✓	✓		✓	(Rajan, Robin and M., 2018; Alwabr *et al.*, 2018)
Cemeteries and livestock burial site	✓	✓	✓	✓	(Üçisik, Rushbrook and Management, 2000; Bryndal, 2015; Neckel *et al.*, 2017)

3.2.3.2 Invasive plant species

Brownfield sites have been colonised by invasive animals and plants that may cause problems for human health and buildings' safety. Research conducted by (Elliott, 2003) considers invasive species as biological pollution where the terms biological pollutants have been used by (Boudouresque and Verlaque, 2002) to discuss the problems caused by such invasive species. According to Mazza *et al*. (2013), invasive alien species are similar to pollutants and maybe even more dangerous than chemicals. They reproduce and spread autonomously and, as a consequence, even if the source of introductions ceases its activity, their negative effects continue and often increase over time. The most common invasive plants in brownfield sites are:

1. Japanese knotweed (*Fallopia japonica*)
2. Himalayan balsam (*Impatiens glandulifera*)
3. Rhododendron (*Rhododendron ponticum*)
4. Giant hogweed (*Heracleum mantegazzianum*).

The first three are a threat to native flora and habitats, as they are aggressive and form dense stands that exclude other plants. In addition, Japanese knotweed can cause considerable damage to buildings, foundations and development sites. If left to establish, the plant can even force its way through tarmac and expose weaknesses or cracks in concrete (Hoxley, 2012). By comparison, Giant hogweed is less aggressive to other plants but is poisonous and can cause severe skin reactions (Rzymski, Klimaszyk and Poniedziałek, 2015)

3.2.3.3 Invasive animal species

Not all invasive animal species pose a risk to human health in brownfield sites, this section highlights some of the most dangerous forms reported (Clavero and García-Berthou, 2005). For humans, one of the most dangerous effects of invasive alien species in brownfield sites is as a carrier of the disease. Biting insects like the Asian tiger mosquito has been linked to more than 20 diseases, including yellow fever and chikungunya fever. Additionally, at least 20 alien mites can transmit viruses to humans (e.g. several ticks of the genus Hyalomma transmit Rickettsia) (Mazza *et al.*, 2013).

3.2.3.4 Human health hazards

Toxic effects can generally be divided into those that result from short–term (i.e. acute) exposure to a substance and those due to doses administered over a longer period (i.e. chronic exposure) (Barry, 1991). Guard (1985) indicated that symptoms resulting from acute exposures usually occur during or shortly after exposure to a sufficiently high concentration of a contaminant. Acute hazards (from materials such as free cyanides, arsenic, phenols and sulphates) are of prime concern to the safety of site workers who may risk exposure for short periods to high concentration. While the term "chronic exposure" generally refers to exposures to "low" concentrations of a contaminant over a long period. Chronic hazards (from such contaminants as arsenic, phenols, some hydrocarbons and polychlorinated biphenyls (PCBs), organic materials and heavy metals) are more affect later residents and long-term.

3.3 Review of Tools that may be Appropriate for Brownfield Sites Assessment

This Section aims to systematically appraise existing risk assessment tools for contaminated sites, regarding the degree of comprehensiveness from low to high (preliminary risk assessment, generic quantitative risk assessment and detailed quantitative risk assessment). Furthermore, the review also encapsulates these crucial risk assessment factors: harm types, hazards category, receptors nature and varying pathways. Thereby pave a path for further research, based on the identified knowledge gaps. This is achieved by the following key objectives:

- To establish the state-of-the-art of existing risk assessment tools of contaminated sites.
- To define knowledge gaps in the current approaches particularly regarding preliminary risk assessment
- To formulate recommendations on how the knowledge gaps could be bridged to develop more appropriate preliminary risk assessment tools.

3.3.1 Scope of the Review

- In this review, risk assessment tools can be any software, methods or numerical analysis models used to qualify or quantify the risk posed from contaminated sites.
- This covers human health, groundwater and buildings as receptors; whereas, other components of the environment (such as air/atmosphere, contaminated vegetables or animals/biotics) are excluded.

The scope of this systematic review is presented in Figure 3:*6*.

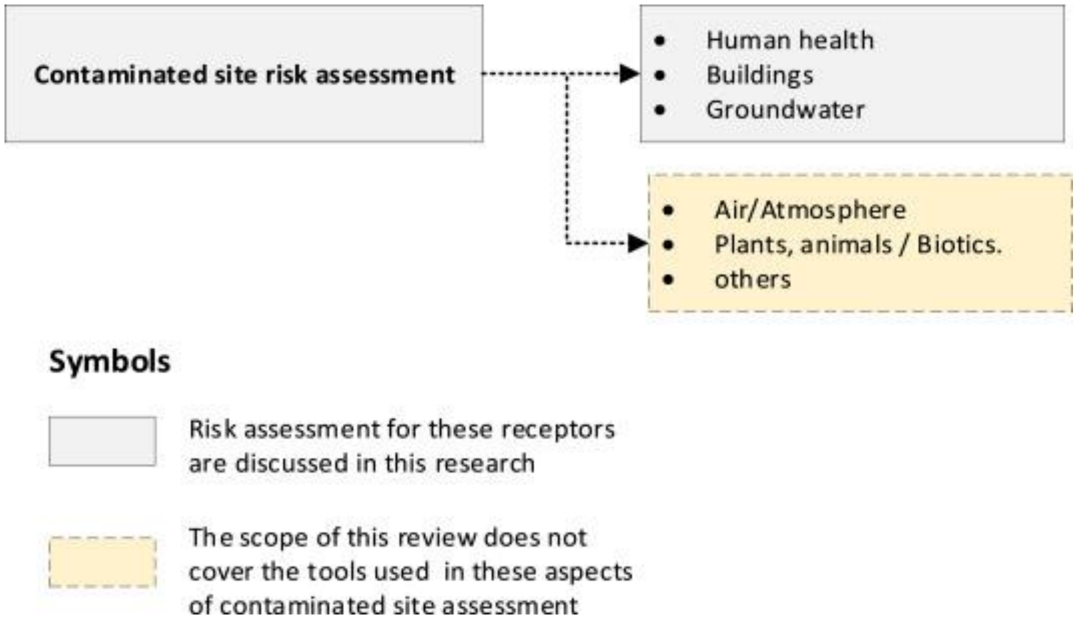

Figure 3:6 Scope of the review

3.3.2 Review Strategy and Selection Criteria

A systematic review (guided by the PRISMA process) was conducted on academic databases, including Scopus, ICE virtual library, and the American Society of Civil Engineers (ASCE), amongst other leading literature database facilities. The keyword selection was divided into two blocks: (1) the "tool" search, which included two elements: "risk assessment" and "assessment tool"; and (2) the "contaminated sites" search, which included four elements: "contaminated site", "human health", "groundwater" and "buildings". "OR" operator was used between the terms in each search and then "AND" operator between the two searches, such that selected articles should include at least one element of each section.

After duplicates were excluded from the multiple searches, all articles were checked and screened based on the following eligibility criteria:

- Select just tools that have been cited by peer review.
- Reviews consider the latest version of the tools and earlier versions are not included.
- Availability of support, ask if there are extensive documentation or help files available to assist users with issues they encounter.

Once a list of tools was identified, content analysis was undertaken to examine each tool based on six main categories (Table 3.4). The first category presents general information about characteristics of the collected tools. Second category selects the appropriate tool for each stage of risk assessment of contaminated sites. Third category identifies the harms considered by each tool. Fourth category determines the type of hazards considered by each tool. Fifth category selects the receptor considered by each tool. Sixth category determines the pathway considered by each tool.

Table 3.4 The main categories used to analyses the tools.

Characteristics of the tools	General information about the tool **Author** **Year** **Tool name** **Year of publication**
Risk assessment stage	What tools used in preliminary risk assessment stage? What tools used in generic quantitative risk assessment? What tools used in detailed quantitative risk assessment? What approach relevant to each tool?
Harm types	What is the harm considered by the tool? **Toxic:** inclusion any substance that may cause toxic **Non–Toxic**: inclusion any harms from explosion, fires or injuries etc.
Hazard types	What is the type of hazard considered by the tool? **Chemical hazards**: hazards related to chemical substances example: metals and organics **Physical hazards**: hazards related to buried services (underground services and storage tanks etc.) **Biological hazards**: hazards such as virus, bacteria etc.
Receptor types	What is the receptor considered by the tool? **Human health:** this may include site workers, residents **Buildings**: the foundations may be affected by the contaminated sites **Groundwater**: contaminants could migrate into aquifer
Pathway types	How receptors can be affected or exposed by contaminants (Ingestion, inhalation, dermal contact for human health and leaching for environmental health for example groundwater)

3.3.3 Identified Tools

The preliminary search results through databases identified 222 articles, with 151 articles identified through grey literature. Based on the methodology section's process, this screening process has reduced the tools to 31, which were included for the final review.

Figure *3:7* presents a synthesis of the literature selection steps, as well as a combined quantitative and qualitative approach was taken to further classification and analysis.

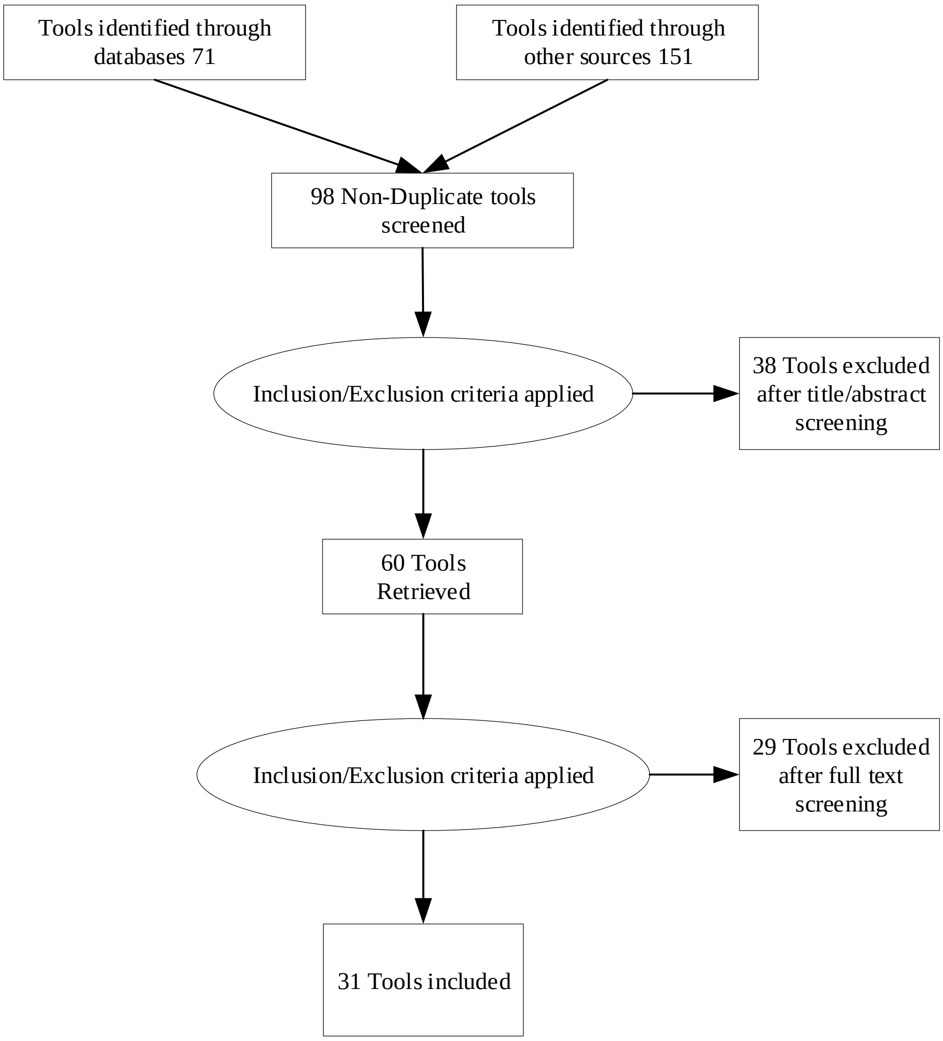

Figure 3:7 PRISMA selection process used for the identification of the tools reviewed in this study.

3.3.4 Characteristics of the Selected Tools

Details of the risk assessment tools (n=31) derived from the PRISMA search are summarised in Table 3.5. This shows the origins of the risk assessment tools are mostly derived from the USA (n=17) and UK (n=9) and accounts for more than 80%; whereas, Denmark (n=3), Spain (=1) and the Netherlands (n=1) account for the remainder. Since 1996 there has been between 1–3 risk assessment tools produced per year, except for 2019, which saw a spike in the number of tools produced (n=8).

Table 3.5 Existing contaminated site risk assessment tools.

#	Year	Country	Tool name	Author(s)
1.	2019	UK	ATRISK	Atkins
2.	2019	USA	IRIS	US National Library of Medicine
3.	2019	USA	ToxRefDB	(Watford *et al.*, 2019)

4.	2019	USA	HERO	US Environmental Agency
5.	2019	Denmark Spain	–	Locatelli *et al*.
6.	2019	USA	BMDS	Jeff *et al*.
7.	2019	USA	Toxicological Profiles	Agency for Toxic Substances and Disease Registry (ATSDR)
8.	2017	UK	Groundwater Vulnerability maps	Environment Agency
9.	2015b	UK	LQM Roadmaps	Land Quality Management
10.	2015	USA	RBCA	American Society for Testing and Materials (ASTM)
11.	2012	UK	GasSim	Environment Agency and Golder Associates
12.	2011	USA	RISC (v5)	Spence and Walden
13.	2011	Denmark	Discrete Dracture	Chambon *et al*.
14.	2009	UK	CLEA	Environment Agency
15.	2009	USA	FOOTPRINT	Noman, Wilson; and Mingyu
16.	2008	USA	ACToR	(Judson *et al.*, 2008)
17.	2008	USA	ARAMS	U.S. Army Engineer Research and Development Center (ERDC)
18.	2008	Denmark	CatchRisk model	Troldborg *et al*.
19.	2008	Spain	SRC-DSS	López *et al*.
20.	2007	Netherlands	CSOIL	Brand, Otte and Lijzen
21.	2006	USA	SADA	The Institute of Environmental Modelling (TIEM)
22.	2006	USA	BioBalance	Savannnah River National Laboratory and U.S. Departement of Energy
23.	2006	UK	–	Martin and Toll
24.	2005	USA	AALM	U.S. Environmental Protection Agency
25.	2005	UK	–	Bonniface *et al*.
26.	2003	USA	3MRA	U.S. Environmental Protection Agency
27.	2003	UK	LandSim	(Environment Agency and Golder Associates, 2003)
28.	2003	UK	ConSim	Environment Agency
29.	2002	USA	EMSOFT	US Environmental Protection Agency
30.	1997b	USA	3DFATMIC	Gour-Tshy *et al*.
31.	1997a	USA	2DFATMIC	Gour-Tshy *et al*.

3.3.5 Analysis and Discussion

More comprehensive analysis of the reviewed tools is conducted and illustrated in Table 3.6.

Table 3.6 Analysis of the risk assessment tools

	Risk assessment stages			Harms		Hazards categorization			Receptors			Pathways
	PR[A]	GQRA[B]	DQRA[C]	Toxic	Non – toxic	Chemical hazards	Biological hazards	Physical Hazards	Human health	Building materials	Ground –water	

1.		✓		✓		✓			✓			1,2,3,4,5,6
2.		✓		✓		✓			✓			1,4, 5
3.	✓			✓		✓			✓			1,2,4,5
4.		✓		✓		✓			✓		✓	1,2,3,4,5,7
5.			✓	✓		✓					✓	7
6.			✓	✓		✓			✓			1,2,4,6
7.		✓		✓		✓			✓			1,2,4,5,6
8.	✓			✓		✓					✓	7
9.			✓	✓		✓			✓			1,2,3,4,6
10.			✓	✓	✓	✓			✓		✓	1,2,3,4,5,6,7
11.			✓		✓	✓			✓			1,2,3,4,5,6
12.			✓	✓	✓	✓			✓		✓	1,2,3,4,5,6,7
13.			✓	✓		✓					✓	7
14.		✓	✓	✓		✓			✓			1,2,3,4,5,6
15.			✓	✓		✓					✓	7
16.	✓			✓		✓			✓			1,2,4,5
17.			✓	✓		✓			✓		✓	1,2,3,4,5,6,7
18.			✓	✓		✓					✓	7
19.	✓			✓		✓			✓			1,2,3,4,5,6,7
20.			✓	✓		✓			✓			1,2,3,4,5,6
21.			✓	✓		✓			✓		✓	1,2,3,4,5,6,7
22.			✓	✓		✓					✓	7
23.	✓			✓	✓	✓		✓	✓	✓		1,2,3,4,5,6,7
24.			✓	✓		✓			✓			1,2,4,5,6
25.	✓			✓		✓			✓	✓		1,2,3,4,5,6
26.			✓	✓		✓			✓		✓	7
27.			✓	✓		✓					✓	7
28.			✓		✓	✓					✓	7
29.			✓	✓		✓			✓			6
30.			✓	✓		✓	✓				✓	7
31.			✓	✓		✓	✓				✓	7

A= Preliminary risk assessment; B=Generic quantitative risk assessment; C= Detailed quantitative risk assessment; 1=Direct Soil ingestion; 2= Dust ingestion; 3= Consumption of homegrown produce; 4= Inhalation of dust; 5= Dermal contact with soils; 6= Inhalation of vapours;7=Leaching to pore water

3.3.5.1 Tools corresponding to risk assessment stages

As observed from the column of risk assessment stages in Table 3.6, most tools are developed for DQRK by twenty tools, followed by five tools for GQRA. Only three tools for PRA. Further analysis is presented in Table 3.7, which indicates methods used to develop risk assessment tools are diverse and are classified in this study into five types including databases, fate and transport, exposure assessment, maps and dose-response.

Table 3.7 Distribution of tools by risk assessment process and adopted approach

	Fate and transport models	Exposure assessment models	Databases	Dose response	Maps
Applies to these degrees of risk assessment. ⇨	DGRA	PRA, GQRA and DGRA	PRA and GQRA	DGRA	PRA
1.		✓			
2.			✓	✓	
3.			✓		
4.			✓		
5.	✓				
6.				✓	
7.			✓		
8.					✓
9.				✓	
10.	✓	✓			
11.	✓				
12.	✓	✓			
13.	✓				
14.		✓			
15.	✓				
16.			✓		
17.		✓			
18.	✓				
19.	✓	✓			
20.		✓			
21.		✓			
22.	✓				
23.			✓		
24.		✓			
25.			✓		
26.		✓			
27.	✓				
28.	✓				
29.	✓				
30.	✓				
31.	✓				

Figure 3:*8* shows that three approaches are used for preliminary risk assessment of contaminated sites, including databases (four tools), exposure (one tool) and maps (one tool). While the approaches used in generic quantitative risk assessment are exposure assessment models (two tools) and databases (three tools). Finally, detailed quantitative risk assessment used diverse approaches including fate and transport models (13 tools), followed by exposure assessment models and dose-response by 6 tools and 2 tools, respectively.

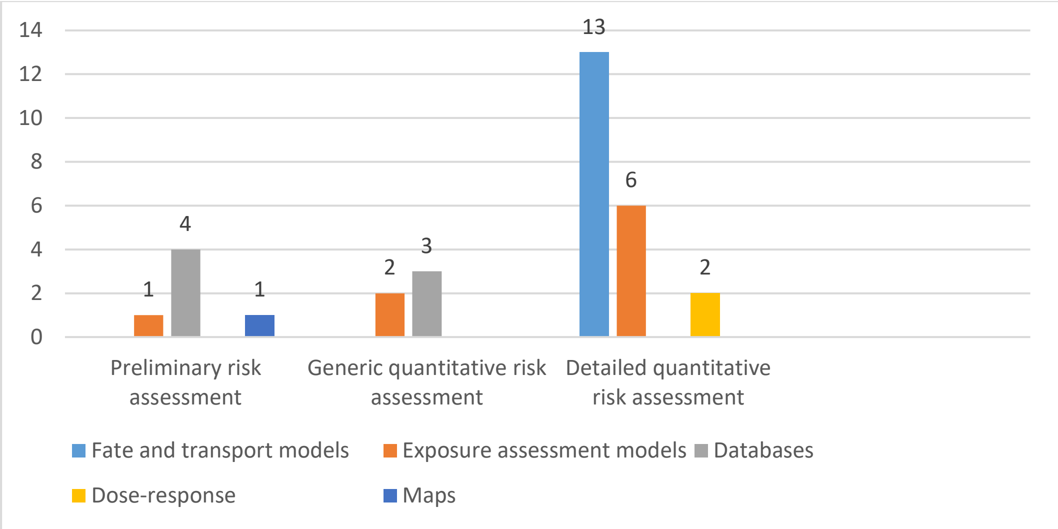

Figure 3:8 Classification of tools based on the approach adopted

Despite much development of tools based on the fate and transport approach, there is still a disappointing success and lack of well–established tools that encourage preliminary risk assessment. However, fate and transport approaches need considerable volumes of data and a large amount of work to set up, which is time-consuming with a high cost of investigation in managing thousands of contaminated sites (Smith, 2005; Locatelli *et al.*, 2019). Otherwise, one of the key limitations to adopt exposure assessment models, databases, dose-response models in the preliminary risk assessment is the uncertainties associated with the interpretation of toxicological information are likely to continue unless the development of comprehensive and easy to use tools enable assessors to reduce their uncertainty and boost their confidence in making decisions. For example, a developer may decide to use a remediation option to bring a site up to standard higher than is strictly necessary to protect human health. This implies that "over remediation" leads to excessive cost for developers (Environment Agency, 2008; Nathanail *et al.*, 2015; Swartjes, 2015; Locatelli *et al.*, 2019).

3.3.5.2 Risk assessment tools by harm types

Figure 3:9 shows twenty nine of the tools addressed toxic harms, which can generally be divided into those that result from short-term (i.e. acute) exposure to a substance and those due to doses administered over a longer period (i.e. chronic exposure) (Barry, 1991). Acute hazards (from materials such as free cyanides, arsenic, phenols and sulphates) are of prime concern to the safety of site workers who may expose to risk for short periods to relatively high concentration. While the term "chronic exposure" generally refers to exposures to "low" concentrations of a contaminant over a long period. Chronic hazards (from such contaminants as arsenic, phenols, some hydrocarbons and polychlorinated biphenyls (PCBs), organic materials and heavy metals) mostly affect the later residents and long term occupants of land (Leach and Goodger, 1991). It is noticeable that the existing tools do not explain how the human body will respond when exposed to the toxic dose. In addition, the tools are based on animals' studies and human volunteers. So the benchmarks in the tools are not based on dose intake directly by children but an extrapolation of the data in the epidemiological studies of humans and animals (Environment Agency, 2009a), which raises the level of safety to higher standards than is strictly necessary to protect children health (Hong, 2015). Otherwise, only five tools addressed non–toxic harms, such as fire and suffocation hazards.

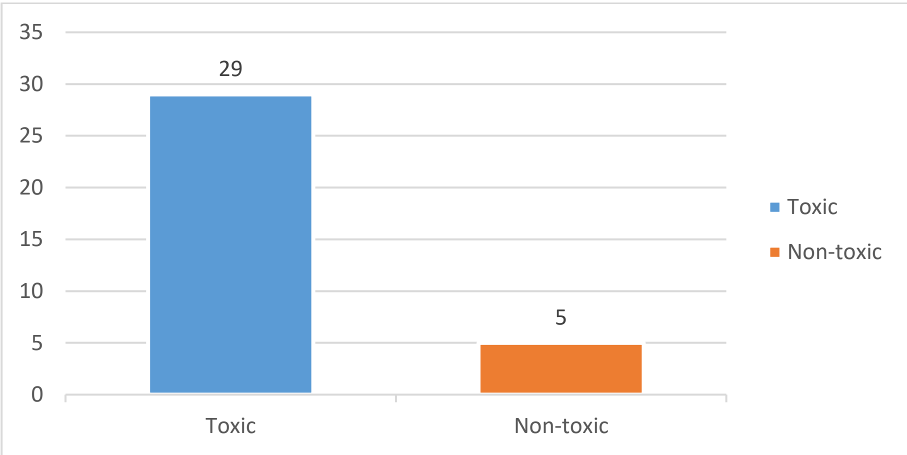

Figure 3:9 The Distribution number of tools by harm type

3.3.5.3 Risk assessment tool by hazard types

Development on contaminated sites presents a huge hazard considering the difficulties to develop because of their constraints including physical, chemical and biological hazards (Charles *et al.*, 2002). As reported by (Skinner, Charles and Tedd, 2005), physical hazards are regarded as geotechnical, and chemical and biological hazards are considered to be geoenvironmental. The review shows an absence of tools that address physical problems, including buried foundations and settlement of filled ground (Watts and Charles, 2015). Otherwise, most tools are designed to assess chemical contamination that may cause long–term threat to human health through ground, groundwater or plants. In addition, a number of studies (Sarsby, 2000; HSE, 2018) conclude that contaminated sites could be a source of biological hazards, which may lead to serious disease, only a few risk assessment tools address biological hazards (Figure *3:10*).

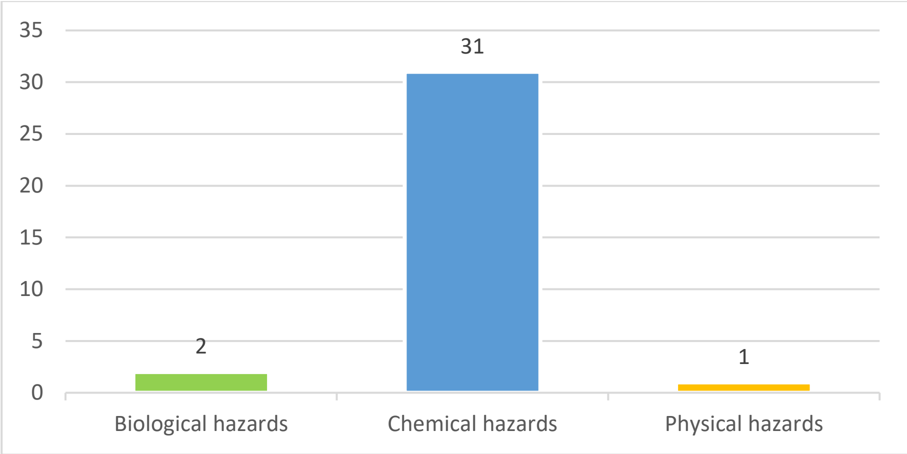

Figure 3:10 The distribution of tools separated by hazard category

3.3.5.4 Risk assessment tools by receptor types

Figure 3:*11* shows a considerable number of tools are developed to address the human health issues associated with contaminated sites, which is understandable as the human wellbeing is a stakeholder's priority. In addition, the review shows an important number of tools could be applied to assess risks from a contaminated site to the groundwater. It is essential to bring the attention of the reader that groundwater, surface water and air are considered in some tools like receptors of the contaminants but may also act as pathways, via consumption of water, inhalation of air to a human receptor (Leach and Goodger, 1991; Laidler, Bryce and Wilbourn, 2002; Nathanail and Bardos, 2005; Syms, 2007). For example, LanSim tool is used to assess risks of groundwater pollution from landfill by simulating the migration of contaminants from landfill site to groundwater over time and estimate pollutant concentration in groundwater (Mishra *et al.*, 2017). Otherwise, risk assessment tools of buildings in contaminated sites are not covered.

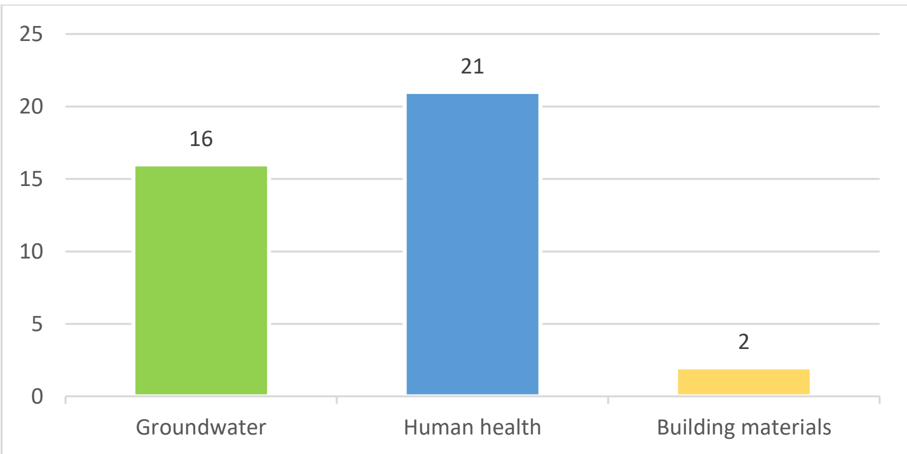

Figure 3:11 The distribution of tools separated by receptor type

3.3.5.5 Risk assessment tools by pathway types

Pathway in this study refers to a route or means by which a receptor can be exposed to, or affected by, a contaminant (Environment Agency, 2004). The same contaminant may be linked to two or more distinct receptor types by different pathways, or various contaminants and/or pathways may affect the same receptor. It must first be noted that a tool can focus on more than one pathway. In terms of volume, Figure 3:*12* shows that most tools (n=19) address direct ingestion and inhalation of dust (n=19), followed by dust ingestion, leaching to poor water and dermal contact with soils (18 tools, 18 tools and 17 tools, respectively). While inhalation of vapours and consumption of homegrown were addressed by 16 tools and 13 tools successfully.

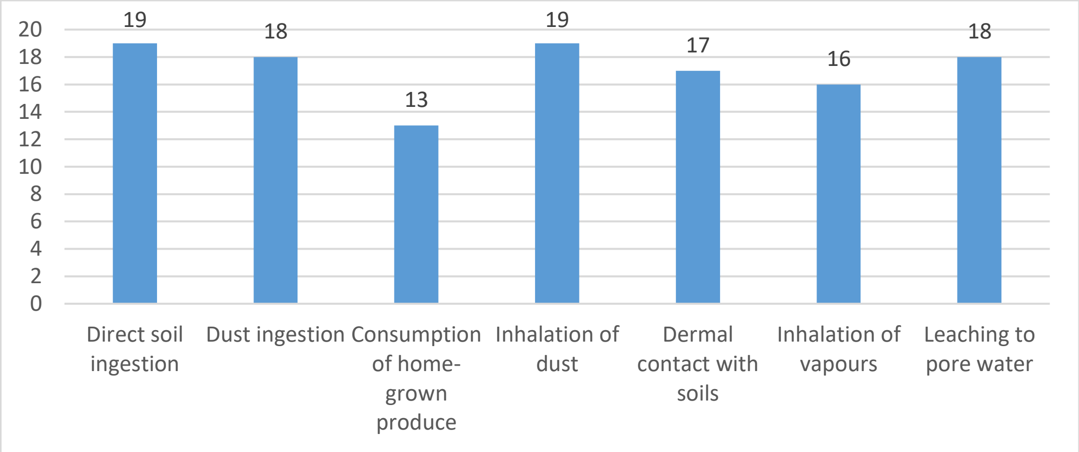

Figure 3:12 The Distribution number of tools by pathways

3.4 Chapter Summary

The chapter was divided into two parts, the first part examined the major hazards associated with brownfield sites where three most common hazards for the built environment are determined with description: physical hazards, chemical hazards and biological hazards. The physical hazards usually related to geotechnical problems including ground movement, obstructions (i.e. buried foundations, underground services, old tanks etc.). Chemical hazards for contamination risk may include hazards from chemical substances and gas migration, which may pose a significant threat to different human health and the built environment. In addition, biological hazards may exist on a brownfield site, including pathogenic micro-organisms and invasive species. The second part systematically reviewed available risk assessment tools sites that could be appropriate for brownfield sites. From a collection of 222 articles, 31 tools were identified for review and classification. The analysis was conducted with respect to the following aspects: risk assessment stages, type of harm, hazard category, receptor type and pathways. From these analyses and the underlying subject of the review, critical discussion was conducted to identify the knowledge gaps. For instance, in the preliminary risk assessment stage, further work is needed to provide more options for brownfield site assessors to use tools. More comprehensive tools are needed to reduce uncertainties in hazards identification, particularly for stakeholders with limited knowledge. Furthermore, most tools address risks to human health and groundwater, while buildings are not considered. Finally, the pathways that are considered are also insufficient. In addition, researchers can make use of this review to define their future directions and efforts in developing better tools. Conversely, based on the existing list of tools reviewed, users can now select the most appropriate one to suit their objectives, needs, and contexts. The next chapter presents the methodology employed in this study.

4. CHAPTER 4: RESEARCH DESIGN AND METHODOLOGY

4.1 Introduction

Based on an extensive review of methodologies and methods, this chapter explains the research methodology as well as the selection and justification of the most appropriate approach to answering the research questions within the study's scope and context. The chapter is divided into four main sections. Section 4.1 provides an introduction to the research methodology chapter. Section 4.2 discusses a number of models that have been developed to conduct research, then deciding the research design of this study, and includes identification of stance adopted with regard to research philosophy (Section 4.3), research approach is taken (Section 4.4) and methodology choice (Section 4.5). Research strategies, time horizons and research techniques are presented in Section 4.6, Section 4.7 and Section 4.8, respectively. While Section 4.9 presents the overall research design, Section 4.10 summaries the chapter.

4.2 Research Design

The Cambridge dictionary (2013) defines the term 'research' as, '*A detailed study of a subject, especially in order to discover (new) information or research (new) understanding'*. According to Fellows and Liu (2015), the basis of any research process is the research design, which guides researchers and readers to understand the principles and procedures of logical thought process applied to the research. A good research design allows researchers to obtain "the best data possible" (Toledo-Pereyra, 2012). Three models have been developed to support the explanation of research design Crotty (1998), Kagioglou *et al.* (2000) and Saunders (2011).

According to Crotty (1998), research should be designed considering the answers to four main questions: (1) What epistemology informs the research? (2) What theoretical perspective underpins the methodology? (3) What methodology governs the choice and use of methods? (4) What methods are proposed? This model is presented in Table 4.1.

Table 4.1 Research design elements as defined by (Crotty, 1998)

Research Design Dimensions	Explanation
Epistemology	Theory of knowledge embedded in the theoretical perspective (e.g. objectivism, subjectivism, constructionism).
Theoretical perspective	Philosophical stance (e.g. positivism and post-positivism, interpretivism, critical inquiry, feminism, postmodernism).
Methodology	Strategy or plan of action that links methods to outcomes (e.g. experimental research, survey research, ethnography, phenomenological research, grounded theory, action research, discourse analysis).
Method	Techniques and procedures (e.g. questionnaire, interview, focus group, case study, statistical analysis, cognitive mapping).

An alternative approach, known as the *nested approach methodology*, was developed by Kagioglou (1998). This model includes three main components (Figure 4:*1*): (i) the first component is the research philosophy, which guides the research approaches and research techniques; (ii) the second component is research approaches, which refers to the organising of research activities, and data collection to the methods for theory generation and testing (e.g. action research, survey and experiment); and (iii) the third component is research techniques, which concerns the data collection techniques (such as interview, questionnaires, focus groups and observation).

Figure 4:1 Nested Research Methodology

Source: Kagioglou (1998), used with permission from Kagioglou

The final model, proposed by Saunders (2011), is known as the research onion model (Figure 4.2). In this model, the research design consists of six layers. It can be clear that this model comprises all the components adopted in the models developed by (Crotty, 1998) and (Kagioglou, 1998), therefore provides assistance in understanding all research components and in adopting an adequate tool to achieve the aim of this research. This present study has adopted the research onion model. This enables the researcher to present a clear design structure of this research, where the six layers of the onion model offer methods from which the researchers may select the most adequate based on the nature of this research.

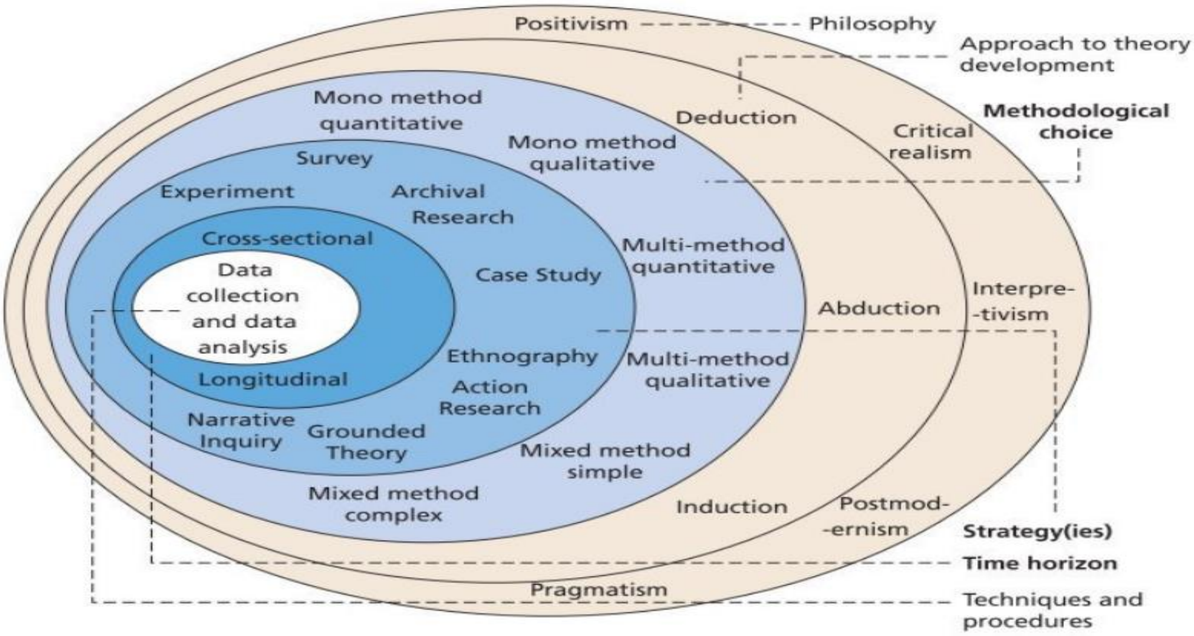

Figure 4:2 The research onion model

Source: Saunders, Thornhill and Lewis (2019) Research methods for Business Students (8th edition) Harlow: Pearson: , p 130. The research onion diagram is ©2018 Mark Saunders, Philip Lewis and Adrian Thornhill and is reproduced in this thesis with their written permission.

4.3 Research Philosophy

In the outermost layer of the research onion, Saunders *et al*. (2009) present the philosophy of conducting research and describe various view of choosing a philosophy. According to Creswell (2009), research philosophy generally represents the philosophical worldview that forms the basis for conceptualising a research problem. Understand research philosophy can help to explain the fundamental assumptions concerning the style in which a researcher sees the world. The research philosophy can be considered under three main categories, including epistemology, ontology and axiology. In addition, Sexton (2004) highlights the different viewpoints of research philosophies, which are illustrated in

Figure *4*:*3*.

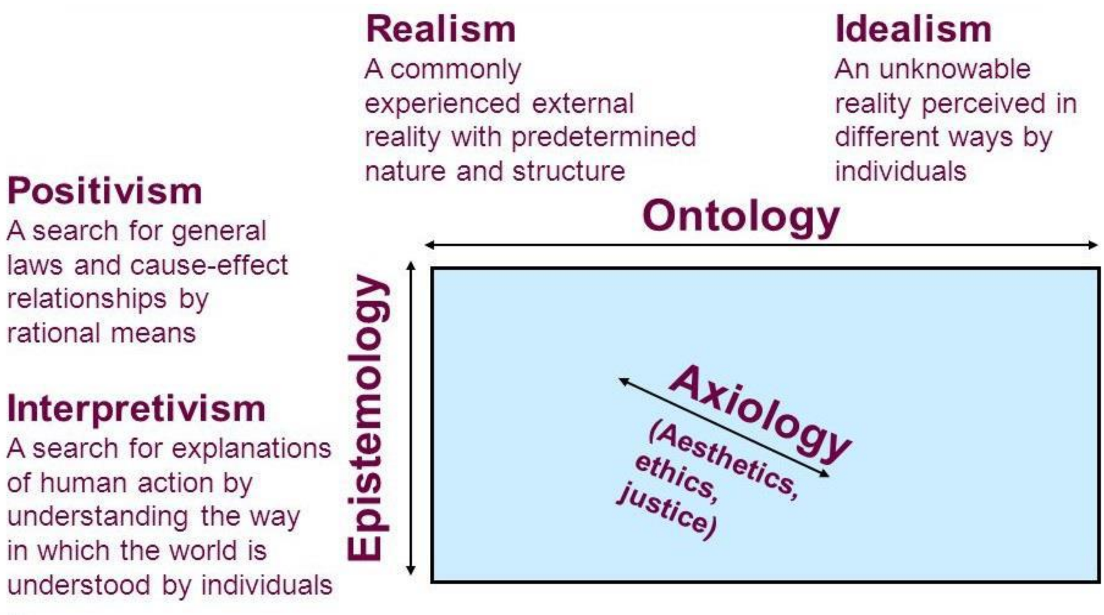

Figure 4:3 The dimension of the research philosophy

Source: Sexton (2004), reused with permission from Martin Sexton

Ontology is concerned with the nature of reality and the assumptions made about the nature of reality from the viewpoint of the researcher (Kanellis and Papadopoulos, 2009). Ontology is mainly related to realism and idealism. Realism is a philosophical position related to scientific enquiry, where reality exists independently of the human mind with predetermined nature and structure (Crotty, 1998; Saunders, Thornhill and Lewis, 2019). Epistemology is concerned with the theory of knowledge. It deals with the nature of knowledge, justification, and the rationality of belief (Williams, 2001). Therefore, epistemology asked questions like ‘how do we know something’ How can you defend what you know? How can you justify what you know? There are two poles in epistemology, namely positivism and interpretivism. Positivism refers to a research paradigm that believes in single reality shared around the world. While interpretivism believes in multiple realities. Therefore, reality is different from its context and the case under investigation (Järvensivu and Törnroos, 2010). Interpretivism is also known as, constructivism idealism or relativism, and is a view of the world as creation of mind. Although the line between positivism and interpretivism is clear at a philosophical level, Easterby-Smith, Thorpe and Jackson (2012) debated that this line may become unclear at a research design level when the researcher needs to understand the real condition from a various viewpoint. The researcher may decide to combine the collected data methods using both qualitative and quantitative approaches to understand the nature of the real world as perceived by those interviewed and/or surveyed which is more suited for this research (Ahmed, Opoku and Aziz, 2016). The axiological stance in research refers to a branch of philosophy studying judgements about value, which are more related to aesthetics, ethics and justice (Sexton, 2004; Saunders *et al.*, 2015).

The researcher is not required to adopt a single paradigm in his research, where mixing paradigms seeks to improve the theory development process, enhance the value and importance of the study and achieve a deeper understanding of reality. Given the rigour and flexibility provided by the critical realism paradigm, the philosophical paradigm of this research sits on pragmatist epistemological position, located between the positivist/realist and constructivist/constructionist epistemologies, where positivist paradigm used to test and generalise the results, while interpretivist paradigm used to construct reality as it is conceived in various cases. Indeed, the researcher takes a sceptical attitude in gaining, validating, verifying and testing knowledge.

4.4 Research Approach

The research approach is concerned with organising research activities, considering the data collection and the data presentation techniques, ensuring that they are most suitable to achieve the research aims (Ahmed, Opoku and Aziz, 2016). It can be seen from the second layer of the onion model above that there are two principle research approaches, the deductive and the inductive. The deductive approach seeks to develop a theory from general evidence to applications. In other words, the theory is produced from the literature and then tested on a community or population. In comparison, the inductive approach seeks to develop the theory from data analysis (Collis and Hussey, 2013; Bell, Bryman and Harley, 2018).

Therefore, the difference between the two research approaches is that deductive is intended to test theory and inductive to build theory. Saunders, Thornhill and Lewis (2009) mention that the deductive approach is close to positivism and inductive to constructivism. In addition, Creswell (2009) indicates that the deductive approach is adequate in case of abundant literature and the possibility to develop a theoretical framework. Therefore, the present study falls into this category and as such, a deductive approach has been adopted.

4.5 Methodological Choice

The methodological choice presented in the third layer of the research onion, including the mono-method, the mixed method and the multi-method. As the names of these methods indicate, the mono-method uses a single research approach to study. The mixed method involves the adoption of both qualitative and quantitative approaches (Twycross, 2004). In the multi-method research, programs include more than one method of collecting data and or more than one method of analysing the data (Lewis-Beck, Bryman and Futing Liao, 2004). Researchers in mixed methods are careful to distinguish multi-method studies' in which data are collected in mixed method from combined methodology (John and Creswell, 2011), while multi method separate segments, each producing a specific dataset; each is then analysed using techniques derived from quantitative or qualitative methodologies. However, qualitative research generates "textual data" (non–numerical) (Jackson, Drummond and Camara, 2007; Jamshed, 2014). Quantitative research, on the contrary, produces "numerical data" or information that can be converted into numbers (Muijs, 2010). The next section will discuss in details each type of research choice.

4.5.1 Quantitative Study

Quantitative research mostly adopts a deductive research approach concerned with hypothesis/theory testing and examining relationships among variables. The research process starts with the formulation of hypotheses or conceptual models, informed by theories and literature, and followed by data collection and analysis to verify the prior formulations (Gray, 2009). This refers to a research method that generally relies on techniques and processes related to facts and figures rather than subjective opinions (Saunders *et al.*, 2007). The significant strengths of quantitative research strategies are that they do not require a long time in data collection and quantitative data analysis techniques are quite familiar. The most widely used quantitative research strategies are experimental designs and survey research.

4.5.2 Qualitative Study

Qualitative research mostly adopts an inductive approach concerned with theory generation and, thus, based on the interpretivist/constructivist paradigm (Sutrisna, 2009). It concerned with words rather than numbers, as they focus on explaining the meaning of a phenomenon (Jackson, Drummond and Camara, 2007). Therefore, it useful in answering research questions relating to how and why (John and Creswell, 2011). In this form of research approach, textual data are most appropriate. The research process starts data collection and analysis to identify themes towards theory creation (Gray, 2009). A major advantage of this approach is that they provide more depth into the phenomenon under investigation. Moreover, it requires a long time to accomplish a data collection. The most widely used qualitative research strategies are ethnography, grounded theory, phenomenology, and case study. Bell, Bryman and Harley (2018) identify the contrasts between qualitative and quantitative research, as presented in Table 4.2.

Table 4.2 Differences between qualitative and quantitative research (Bell, Bryman and Harley, 2018)

Quantitative study	Qualitative study
• Numbers	• Words
• Point of view of researcher	• Point of view of participant
• Researcher is distant	• Researcher is close
• Theory Tested	• Theory Emergent
• Static	• Process
• Structured	• Unstructured
• Generalisation	• Contextual Understanding
• Hard Reliable Data	• Rich Deep Data
• Macro	• Micro
• Behaviour	• Meaning
• Artificial Setting	• Natural Setting

4.5.3 Research Method Adopted

Given that quantitative and qualitative methods are commonly established profoundly and firmly in the pragmatist epistemological position worldview (Badewi, 2016), which is the adopted philosophical position for this research, both methods were adopted to help achieving the present research objectives. Quantitative research approach is adopted to ensure that the framework and the DSS can assist brownfield site developers and other stakeholders to clarify and anticipate the potential hazards associated with the development of brownfield sites. Qualitative method involves testing tool inputs and outputs against real-life case studies to verify the accuracy of the data output.

4.6 Research Strategy

The research strategy is presented in the third layer of the research onion. It refers to the ways in which to conduct the research, where researchers can use one or more strategies within their research design as they plan how to answer research questions. Therefore, determining the research question is important to select the appropriate data needs to be collected and the appropriate analysis methods. According to Yin (2017), research strategy is designed to reflect on the research topic (what questions) and to address the need for the research (why questions). The strategy can include several different approaches, such as experimental research, action research, case study research, interviews, surveys, and/or a systematic literature review. It is important to note that, although the availability of many research strategies, Saunders (2011) debated that no research strategy is superior or inferior to any other. The next section will define and justify the adoption strategies.

4.6.1 Experiments

The experimental is a systematic and scientific approach to research to predict and investigate probability and causality among chosen variables (Cooper and Yoo, 2013). Empirical research is usually associated with quantitative studies and is frequently employed in a positivist research context. The limitation of this type of research comprises uncertain samples, findings that can only be applied to one case and may be hard to repeat, and finally, difficulty in assessing human response. This research can be time consuming and expensive, which precludes their use in cases where the research requires large samples (Dakhil, 2017). In addition, there may be several areas where experiments cannot be utilised due to ethical and practical considerations. Therefore, this method was not considered convenient because its fundamental aim is to examine the application of a new thing in a new setting, such an aim is not required for this study that does not empirically test.

4.6.2 Survey

Survey is a research strategy used to collect data to test concepts and to explain the attitude and behaviours of the subject (Jackson, 2015). Oates (2005) indicates that this research strategy based essentially on quantitative data and quantitative analysis methods when looking for responses to its research questions, therefore, the survey is appropriate for a positivist paradigm. Methods of data collection include personal interviews, telephone, postal or online. The advantages and disadvantages of this research strategy are presented in Table 4.3.

Table 4.3 Advantages and disadvantages of survey methods (Source: Jones, Baxter and Khanduja, 2013)

Method of data collection	Advantages	Disadvantages
Personal	• Complex questions • Visual aids can be used • Higher response rates	• Expensive • Time inefficient • Training to avoid bias
Telephone	• Allows clarification • Larger radius than personal • Less expensive or time-consuming • Higher response rates	• No visual aids • Difficult to develop rapport
Postal	• Larger target • Visual aids (although limited) • Lower response rates	• Non–response • Time for data compilation
Online	• Larger target • Visual aids • Quick response • Quick data compilation • Lower response rates	• Non–response • Not all subjects accessible

A survey is considered an appropriate method for this study. More details including sampling and procedures will be discussed later in this chapter. However, this study requires the collection of data from multiple persons to investigate their understanding to fulfil the objectives, it also helps to reach a wide number of respondents.

4.6.3 Archival research

Archival research methods include a broad range of activities applied to facilitate the investigation of documents and textual materials from existing archival records (Ventresca and Mohr, 2017). An example of archival research would be an epidemiologist looking at pandemic institution records from the 1900s to determine the spread of flu symptoms in patients at the time. Therefore, this research strategy was not considered appropriate due to the nature of this problem, which aims to identify and prioritize hazards associated with brownfield sites at a preliminary stage.

4.6.4 Case study

Case study research is a qualitative approach in which the investigator explores a contemporary phenomenon in depth and within its real-life context, particularly when the boundaries between phenomenon and context are not clearly evident (Yin, 2009). Case studies are bounded by time and activity, and thus, data collection with detailed information is done over a sustained period of time (John and Creswell, 2011). case studies focus on investigating a small number of cases rather than many cases (Fellows and Liu, 2015). According to Runeson and Höst (2008), a case can be a single person, subject, group or organisation. A case study design comprises data collection techniques, such as detailed and structured interviews, participant/non–participant observation, documentary materials found in available data sources and others. As this study aims to develop a DSS for preliminary risk assessment of brownfield sites, the tool will be validated against two case studies.

4.6.5 Ethnography

It is a further strategy used for qualitative approach, it is concerned with the study of social life and the behaviours and perceptions that occur within groups, teams, organizations and societies (Reeves, Kuper and Hodges, 2008). Wilkinson (2011) presented ethnography as a data collection tool rather than a research design. This study does not intend to examine the behavioural patterns or physiologies of participants, as in the case of ethnographic studies, so this method was not considered adequate.

4.6.6 Action research

Action research can be defined as “an approach in which the action researcher and a client collaborate in the diagnosis and solving of the problem (Bell, Bryman and Harley, 2018), and is often adopted by individuals who need to enhance their understanding of practice within an organisation. Therefore, it stresses research in action instead of researching an action. However, this type of research strategy is popular in business management and includes people within the organisation to identify problems and suitable solutions; as such, it tends to avoid proposing solutions to predefined problems (Bryman, 2015). This research method was not considered suitable for this study due to the nature of the problem, which aims to develop a decision support system for preliminary assessment of brownfield sites, this does not intend to investigate changes within a social system.

4.6.7 Grounded theory

Grounded theory methodology and procedure have become one of the most influential modes of carrying out qualitative research when generating theory is a principle aim of the researcher (Strauss and Corbin, 1997). It is a general methodology with systematic guidelines for gathering and analysing data to generate or improve the theory. The analytic process consists of coding data, developing, checking, integrating theoretical categories and writing analytic narratives throughout inquiry (Charmaz and Belgrave, 2007). Therefore, this research strategy was not selected due to the nature of the problem whereby the theory has already been established through the literature. Instead, this research seeks to weight the potential hazards associated with brownfield sites via quantitative research methods.

4.6.8 Narrative inquiry

This qualitative research inquiry involves the researcher studying individuals lives based on their written or spoken words or visual representation, which is often retold by the researcher in a chronological account (Andrews, Squire and Tamboukou, 2013). In the end, the narrative combines views from both the participant and the researchers' life in a corroborative manner (Polkinghorne, 2007). Examples are biographies and autobiographies. This research method is not suitable for this study due to the nature of the problem.

4.6.9 Phenomenology

The phenomenological method aims to describe, understand and interpret the meanings of experiences of human life. It focuses on research questions such as what it is like to experience a particular situation (Bloor and Wood, 2006). It is an approach that deals with people's perspectives, beliefs, feelings and emotions. This branch of philosophy tends towards the description rather than analysis (Remenyi *et al.*, 1998). However, this is a commonly used approach in clinical psychology. Therefore, this strategy is not suitable due to the nature of this problem.

4.7 Time Horizons

Time horizon presents the fourth layer of the research onion. It is closely related to the organisation and management of the research and considers the time framework that is intended for completion within the project. Two types of time horizons are identified in the research onion: cross-sectional and longitudinal. According to Saunders and Tosey (2013), the research is mainly considered a phenomenon and should be done at a certain point on time is cross-sectional, while the longitudinal time horizon in the study is conducted over a long period of time. Green, Goldman and Salovey (1993) indicate a great need to define a time horizon for research, that is, the research cannot continue indefinitely. Therefore, Kosow and Gaßner (2008) suggest that cross-sectional study is often related to quantitative research and admits that procedures, such as semi-structured interviewing, represent a cross-sectional design common to qualitative design.

Reflecting on the nature of this present research, which is being conducted as a major aspect of a PhD research thesis that must meet strict university rules for the timely gathering of data and presentation of findings. Therefore, given the time constraints and the nature of the mixed method research, a ‘cross-sectional’ approach will be adopted.

4.8 Research Techniques and Procedures

This study adopted different approaches to analyse the data, which will assist in developing the DSS tool. Table *4.4* shows the main methods utilised in achieving questionnaire objective. The data analysis includes descriptive statistics analysis to describe and present data collected from the online survey, while inferential statistics analysis will be used for advanced analysis. Voting Analytic Hierarchy Process (VAHP) used to prioritise potential hazards.

Table 4.4 Research objectives and the methods to achieve them

Research objectives	Research methods									
	Data collection			Data analysis methods						
	Literature review	Questionnaire	Case study	Reliability test	Descriptive	T-test	Kruskal Wallis	Mann Whitney	Kendall's W	VAHP
To review brownfield site definitions, their scope within the UK legislation context and their assessment process	✓									
To identify potential hazards associated with brownfield site development.	✓									
Examine the state-of-the-art of existing risk assessment models and tools of brownfield sites	✓									
To develop the conceptual framework	✓									
To validate the conceptual framework		✓		✓	✓		✓	✓	✓	✓
To validate the DSS		✓	✓	✓	✓	✓				

4.8.1 Data Collection Methods

4.8.1.1 Literature review

According to Machi and McEvoy (2016), the literature review is a piece of academic writing demonstrating knowledge and understanding of the academic literature on a specific topic placed in context. In addition, the literature review synthesizes current knowledge about the research question. This synthesis is the foundation that allows the research to build a convincing thesis case through logical argumentation. This research involves the following stages of literature review:

- At the beginning of the research, a literature review was conducted to gain knowledge of the current issues in brownfield sites redevelopment and subsequently identify the research problems and form the research aim and objectives.
- After the aim and objectives were determined, a more detailed literature review was conducted on the subject matter to form knowledge regarding the potential hazards in brownfield sites, and the adequate site information to identify the potential hazards, concentrating on the theoretical and fundamental concepts.
- Finally, the literature review justifies, demonstrates, explains, collects data, and validates the research outcomes.

4.8.1.2 Systematic review

A systematic review is a defined as a review of the evidence on a clearly formulated question that uses systematic and explicit methods to identify, select and critically appraise relevant primary research, and reports evidence in a way that allows reasonably clear conclusions to be drawn about what is known and what is not known (Jahan *et al.*, 2016). A systematic review should not be viewed as a review of the literature in the traditional sense, but as a stand-alone research project that explores a clearly defined question, usually derived from a policy or practice problem, using existing studies. In addition, systematic review also differs from other review methods because of its distinct and rigorous principles (Denyer and Tranfield, 2009). This research makes use of this methodology of review to define knowledge gap which will help in define future directions and efforts in developing better tools.

4.8.1.3 Questionnaire design and survey implementation

Two questionnaires were designed and sent out to validate the framework and the DSS tool respectively. The first questionnaire survey was designed based on findings identified from comprehensive literature reviews. It was conducted to seek the professional perspective views in this study. Particularly, the questionnaire survey was carried out to:

1- Examine the information that is important to identify pollutant linkage components (Source-Pathway-Receptor).
2- Prioritize and weight the potential hazards associated with brownfield sites

Quantitative survey approach is chosen because it is easy to deploy, and its use via a free online survey system allows savings of time and money. Furthermore, the questionnaire will be recruited using an online survey tool Qualtrics. The recruitment process promotes the survey by using LinkedIn to share the URL of a Qualtrics survey in brownfields and contaminated lands groups. The first phase participant contact will be on LinkedIn by an email attached with a participant information sheet and consent form. The promotion of the survey on LinkedIn contains all the necessary information, such as how long it takes, the aim of the survey, and request to read the attached information sheet and consent form. However, the participants are asked to read and understand the participant consent and participant information sheet, and then if they are interested, they could proceed via an attached link of the survey.

The survey is divided into four main sections. The first section presents generic questions to determine the participant's background and years of experience. The second Section validates the necessary information to establish pollutant linkage model components, the response varied from 1= Not important to 5 very important. The third Section ranks the hazards associated with brownfield sites, which allows participants to rank a set of items against each other. This type of question has the benefit of requiring respondents to identify how elements or choices compare to each other and determines the most likely ones to them. The fourth section allows the participants to provided comments or suggestions.

In the second questionnaire, the survey was divided into seven sections. The first section comprised generic questions to elicit information about the participants. The second section included questions to determine the attitude of participants to the graphical user interface (GUI) of the DSS. The third section evaluates the ease of use of the DSS. The fourth Section examined the quality of information presented in the DSS. While the fifth section investigates the level of information shown in the DSS. The sixth Section included questions to determine to which the DSS is useful in assisting different stakeholders to make an informed decision about the development of brownfield sites. The final Section asked the participants to provide constructive feedback to the researcher to improve the future version of the DSS tool.

Three academic professionals piloted both online surveys before they were accepted as a final survey, focusing on question construction, this ensured that the questionnaires were meaningful and easy to follow. It is important to mention that ethical considerations were also considered the validation of the DSS tool. Unlike the first survey of the validation of the tool, it was not required from all participants in this survey to have extensive knowledge and experience in the redevelopment of brownfield sites. Participants would need to have some level of experience in brownfield site management.

Rating scales

In risk assessment research, many types of rating scales, e.g., five-point, seven-point, nine-point, were used to collect professional views. However, in brownfield redevelopment research, the Likert scale has been widely used (Zhu et al., 2015; Rink and Arndt, 2016; Weng et al., 2019; Ahmad et al., 2020). This study adopted five-point Likert scales to rate the required information to establish pollutant linkage components (Source-Pathway-Receptor), it was also used to validate the DSS tool. Table 4.5 presents the five-point Likert scales adopted in the different sections of the questionnaire. In this research, Likert items are considered an interval level data with distance between the points. Therefore, the data analysis decision for Likert scale items can use the mean to measure central tendency.

Table 4.5 Five-point Likert scales used in both survey questionnaires (derived from Pimentel, 2010)

Likert Scale	Interval	Linguistic terms				
1	1.00-1.79	Not at all important	Excellent	Extremely unclear	Extremely difficult	Not all useful
2	1.80-2.59	Slightly important	Good	Somewhat unclear	Somewhat difficult	Slightly useful
3	2.60-3.39	Moderately important	Average	Neither clear nor unclear	Moderately useful	Moderately useful
4	3.40-4.19	Very important	Poor	Somewhat clear	Very useful	Very useful
5	4.20-5.00	Extremely important	Terrible	Extremely clear	Extremely useful	Extremely useful

4.8.1.4 Data sampling

To determine who will be selected as participants, the survey will adopt a purposive sampling technique. A purposive sample referred to as a judgmental or expert sample, is a type of nonprobability sample, in which researcher depends on his or her judgment when selecting members of people to participate in the study (Saunders, 2011). The purposive sampling is used because the researcher seeks to capture solid knowledge in a particular form of expertise and become better informed about the subject at hand before engaging in tool development.

As discussed in Chapter 2, brownfield sites cover a range of branch of knowledge such as environment, geology, hydrology, geotechnics and chemistry. Subsequently, it is likely to have a wide range of experts from various backgrounds relating to the development of brownfield sites. Consequently, it was decided to obtain a representative from the many specialised professions with a useful contribution to research. Participants in the survey have knowledge and experience in the management process of brownfield sites. These will be selected from the main brownfield groups on LinkedIn. These groups included Brownfield Briefing (739 members), Property and Real Estate Development, Town Planning, Design, Funding and Construction Solution (5825 members), CABERNET– Europe's brownfield regeneration network (member 548), UK Brownfield Investigation Assessment and Remediation (812 members), Construction Industry Research and Information Association (CIRIA) (3000 members), Florida Land Development News (343 members).

As this survey is intended to recruit as many views as possible, hence it is tough to define sample size for this research because it is unknown. Therefore, it is impossible to decide any sample size. However, this research will seek to invite the maximum number of participants from different backgrounds to increase generalization.

4.8.2 Data Analysis

Data collected from the questionnaire surveys were analysed using different statistical analysis methods described in the following sections.

4.8.2.1 Reliability test–Cronbach's alpha

Cronbach's alpha test remains one of the most popular methods for assessing the reliability, or internal consistency, of a set of scale or test items. It is computed by correlating the score for each scale item with the total score for each observation and then comparing that to the variance for all individual item scores. Data is said to have high reliability if it produces similar results under consistent conditions. The Cronbach's alpha coefficient value ranges from 0 to 1, and the higher the value, the more reliable is the adopted scale of measurement. However, Tavakol and Dennick, (2011) argued that, if the alpha value is above 0.70, it indicates an excellent internal consistency within the data. Using SPSS, the Cronbach's alpha coefficient value could be calculated as following (Darko, 2019)

$$\alpha = \frac{N \cdot \bar{c}}{\bar{v} + (N - 1) \cdot \bar{c}}$$

Where:

- N=the number of items
- $\bar{c}$= average covariance between item–pairs
- $\bar{v}$= average variance

In this study, Cronbach's alpha coefficient test was used to assess the reliabilities of the five-point rating scales used to capture the survey responses. Cronbach's alpha coefficient test results are presented and discussed in Chapter 6.

4.8.2.2 Descriptive analysis

Descriptive statistics help to simplify large amounts of quantitative data sensibly. This type of analysis used to organize and describe data (Holcomb, 2016). They provide simple summaries about the sample and the measures. Together with simple graphics analysis, they form the basis of virtually every quantitative analysis of data. Frequency analysis is part of descriptive statistics that deals with the number of occurrences (frequency) and analysis measures of central tendency, percentiles, etc. Measures of central tendency contain the mean, median and mode (Kumar and Chaudhary, 2010). While the mean is the average value of the data set, the median is the middle observation with an equal number of value lying above and below in the data set. Mode is the value that occurs the most number of times in a data set. Standard deviation is a measure of the amount of variation or dispersion of a set of values. Moreover, Frequency Analysis commonly uses percentile values like Quartiles, Deciles, Percentiles, etc.

Each descriptive statistic reduces many data into a more straightforward summary that the reader has an idea of the data through a graphical or pictorial presentation. However, descriptive statistics are typically distinguished from inferential statistics (Holcomb, 2016). With descriptive statistics, researchers simply describe what is or what the data shows. While inferential statistics, researchers are trying to reach conclusions that extend beyond the immediate data alone. In this study, a descriptive analysis will summarise a given data set in terms of mean, median, standard deviations and percentiles.

4.8.2.3 Inferential analysis

After conducting descriptive statistics to find out the mean and looking at the data distribution, it is important to make inferences about the data. These statistical tests allow researchers to make inferences because they can show whether an observed pattern is due to intervention or chance (Jackson, 2011). There is a wide range of statistical tests, the decision of which statistical test to use depends on the research design, the distribution of the data, and the type of variable. In general, if the data is normally distributed, parametric tests should be used. If the data is non-normal, non-parametric tests should be used (Hecke, 2012).

4.8.2.3.1 Data normality test– Shapiro-Wilk

The Shapiro-Wilk test examines if a variable is normally distributed in a population. The null hypothesis of the Shapiro– Wilk test is that the data were normally distributed. The test rejects the hypothesis of normality when the p-value is less than or equal to 0.05, and conclusion that the data are not normally distributed must be made. In this research, all the p-value calculated by the Shapiro-Wilk test was less than 0.05, which confirmed that the collected data were not normally distributed. This is expected because for small sample sizes, the sampling distribution of the mean is often non-normal distributed (Royston, 1992).

4.8.2.3.2 Concordance test – Kendall's coefficient of concordance

Kendall's coefficient of concordance (also known as Kendall's W) test is a non-parametric statistic. It was conducted to check agreements among the participants regarding the site information's ranking for preliminary risk assessment and the potential hazards associated with brownfield sites. It is a normalization of the Friedman test statistic and can be used for assessing agreement among raters (Rasli, 2006). Kendall's W tests the null hypothesis that "no agreement exists among the rankings given by the participants in a particular group". It ranges from 0 (no agreement) to 1 (complete agreement) (Lewis and Johnson, 1971).

$$W = 12 \sum \frac{R_i^2 - 3k^2N(N+1)^2}{k^2N(N^2-1) - k\sum T_j}$$

Where: $\sum R_i^2$ is the sum of the ranks for the individual ranked N factors object; k is the total number of participants or rankings; and $k\sum T_j$ is the sum of values of T_j over all k sets of ranks.

4.8.2.3.3 Intergroup comparison – Kruskal-Wallis H test

As the participants were from different backgrounds (Geotechnical engineering, geologists, hydrologists, etc), it was fundamental to check whether there were significant differences between them, by applying intergroup comparisons. To conduct the intergroup comparisons, two different statistical methods were considered ANOVA and Kruskal–Wallis H test, where ANOVA test is the parametric equivalent of the Kruskal-Wallis H test (Hecke, 2012). Consequently, due to the non–normal distribution of the collected data, the Kruskal-Wallis H test was selected rather than ANOVA to carry out the intergroup comparison in this study. Briefly, the Kruskal-Wallis is a nonparametric statistical test that assesses the differences among three or more independently sampled groups on a single, non-normally distributed continuous variable. Non-normally distributed data (e.g., ordinal or rank data) are suitable for the Kruskal-Wallis test (McKight and Najab, 2010). The outcome of this test identifies differences among the groups but does not identify which groups are different from other groups. To determine which groups are different from others, post–hoc testing can be conducted. Elliott and Hynan (2011) indicated that the most common post–hoc for the Kruskal-Wallis H test is the Mann–Whitney U test.

4.8.2.3.4 Mann-Whitney U test

Mann-Whitney U test is used in this study to perform multiple pairwise nonparametric comparisons if the Kruskal-Wallis H test shows a significant difference among participants. However, the Mann-Whitney U test is used to compare differences between two independent groups when the dependent variable is either ordinal or continuous, but not normally distributed (McKnight and Najab, 2010).

4.8.2.3.5 T-test

The one-sample t-test is used to compare the significance means of two groups. The null hypothesis (H0) is that the true difference between these groups means is zero. While the alternate hypothesis (Ha) is that the true difference is different from zero. The one-sample t-test is conducted at a 95% confidence level with a 0.05 p-value. The null hypothesis for a factor should be rejected if its p-value is lower than 0.05 (Semenick, 1990; Kim, 2015).

4.8.2.4 Voting Analysis Hierarchy Process

VAHP is a Multi-Criteria Decision-Making (MCDM) method proposed in a study by Liu and Hai (2005) as a novel easier weighting procedure in place of AHP's paired comparison. The study integrated VAHP-DEA methodology to evaluate alternatives. The data envelopment analysis (DEA) method was adopted to aggregate votes each criterion received in different ranking places into an overall score of each criterion. The overall scores were then normalised as the relative weights of criteria (Hadi-Vencheh and Niazi-Motlagh, 2011). They used equation known as Noguchi's model (Noguchi, Ogawa and Ishii, 2002) to determine weights of criteria. Nevertheless, the VAHP maintained the main concept of AHP which is to divide complex problems into a hierarchy of goals, criteria and alternatives to capture the basic elements of the decision problem, followed by criteria and alternatives as shown in Figure 4:*4*. After the hierarchy model was established in the VAHP, the weights of criteria will be calculated through voting instead of using the paired comparisons of the AHP. Liu and Hai's model (LH-model) consists of the following steps:

Step 1: *Determine the framework criteria.* The framework criteria can be obtained from the existing literature or through other methodologies in the initial step.

Step 2: *Structure the hierarchy of the criteria,* in the second step, developing a multi-level hierarchy model, which will provide the user with a better understanding of the interrelationship of the entire assessment framework

Step 3: *Vote on the importance of criteria and sub-criteria.* In this step, it is required to rank order the criteria by experts based on their importance.

Step 4: *Derive the importance ratings of criteria and sub-criteria.* In the fourth step, Liu and Hai (2005) have adopted a DEA approach to determine the weight of criteria and sub-criteria by using the following model:

$$\theta_{rr} = \max \textstyle\sum_{(s=1\sim S)} U_{rsX_{rs}},$$

$$\theta_{rp} \textstyle\sum_{(s=1\sim S)} U_{rsX_{ps}} \leq 1(\rho = 1,2, \ldots . R),$$

$$U_{r1} \geq 2U_{r2} \geq 3U_{r3} \geq \cdots \geq SU_{rs},$$

$$U_{rs} \geq \varepsilon = 1/((1 + 2 + \cdots + S) * n)$$

$$= \frac{2}{n*S(S+1)}$$

Equation 1

Where S_{rs}=the total votes for the rth criteria for lth place by n voters. α is the constraint which stands for the difference in weights between sth place and (s+1) th place

Step 5: *Measurement of the performance of alternatives*. In the fifth step, the performance of the alternatives is measured against those criteria and sub-criteria that are represented in the criteria hierarchy. Liu and Hai (2005) provide a detailed explanation of how these measurements have been applied in their case study, which involved both factual data and qualitative judgements.

Step 6: *Identification of the priority of alternatives*. In the fifth step, the total weight obtained in Stage 5 through the summing of criterion weights.

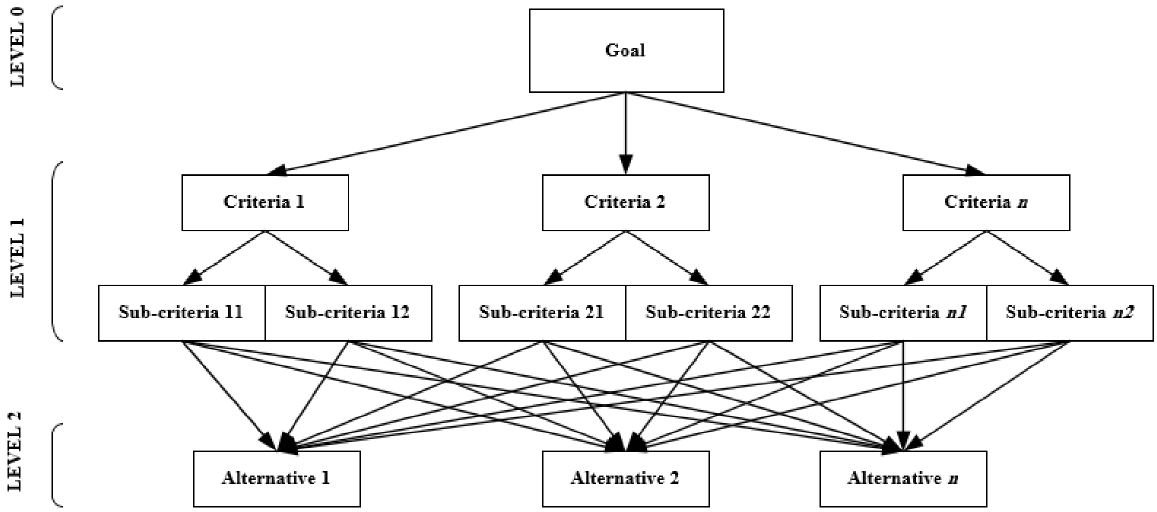

Figure 4:4 Schematic of the Analytical Hierarchy Process

Despite the advantages of Liu and Hai's model (LH–model), some of its limitations were highlighted by Hadi-Vencheh and Niazi-Motlagh (2011). For example, LH–model adopts Noguchi's model, which has the main deficiency, it uses the term 2/ nS (S+1) to bound U_{rs} and giving it a value greater than zero. Therefore, if the number of voters is unknown, the model cannot be used. Also, they mention that AHP can only compare a limited number of alternatives. In this case, the LH–model applies Noguchi's model which has some limitations discussed before. To overcome this dilemma, the Hadi–Vencheh and Niazi–Motlagh mode (HN model) combine the AHP with a new voting DEA model (Equation 1) and propose an integrated VAHP–DEA methodology. In step 5, AHP and LH–model use comparing scores while the HN–model used again 'voting' and proposed an equation (2). Finally, step 6 is the same as in the three methods. So, the difference of LH–model and HN– model VAHP is steps 3, 4 and 5.

$$w_1 \geq 2w_2 \geq 3w_3 \geq \cdots . \geq Sw_s \qquad \text{Equation 2}$$

$$\sum_{s=1}^{S} w_s = 1$$

$$\alpha \leq \theta_r = \sum_{s=1}^{S} x_{rs} w_s \quad r = 1,2, \ldots ., R \qquad \text{Equation 3}$$

Where x_{rs} is the total votes of the rth criteria for the sth place.

The literature shows several methods to solve Multiple–criteria decision–making (MCDM) issues. This research study adopted VAHP to analysis the data collected to validate the conceptual framework. This method first decomposes the decision problem into a hierarchy of subproblems. Then the decision-maker evaluates the relative importance of its various elements by voting. The additional advantages of VAHP that have affected the chose to adopt it for this present study are outlined Soltanifar and Hosseinzadeh Lotfi (2011) below:

- The VAHP method is easy to understand
- It is simple to obtain priority weights
- It complies with the objectives of this present study, in as much as this model does not depend on the number of participants when it comes to its operation. Besides, the number of options for the answers can be equal to the number of places (positions).
- Less time consuming because of the use of vote raking, rather than of paired comparisons.

4.9 Overall Research Design

The research design process is described by Yin (2014) as a logical plan for navigation through the research journey. Research design can be referred to as the master plan adopted upon identifying the appropriate approaches within the layers of research methodological design (Thomas, 2002). Therefore, the research design is the general plan for successfully answering research questions after identifying research philosophy, methods, strategies, and techniques (Creswell *et al.,* 2003). An overview of the research methodology is given in

Figure 4:5, where this research study adopt critical realism (pragmatism) as a research philosophy in the spirit of methodological plurality, which allows retrofitting of methods from competing paradigms.

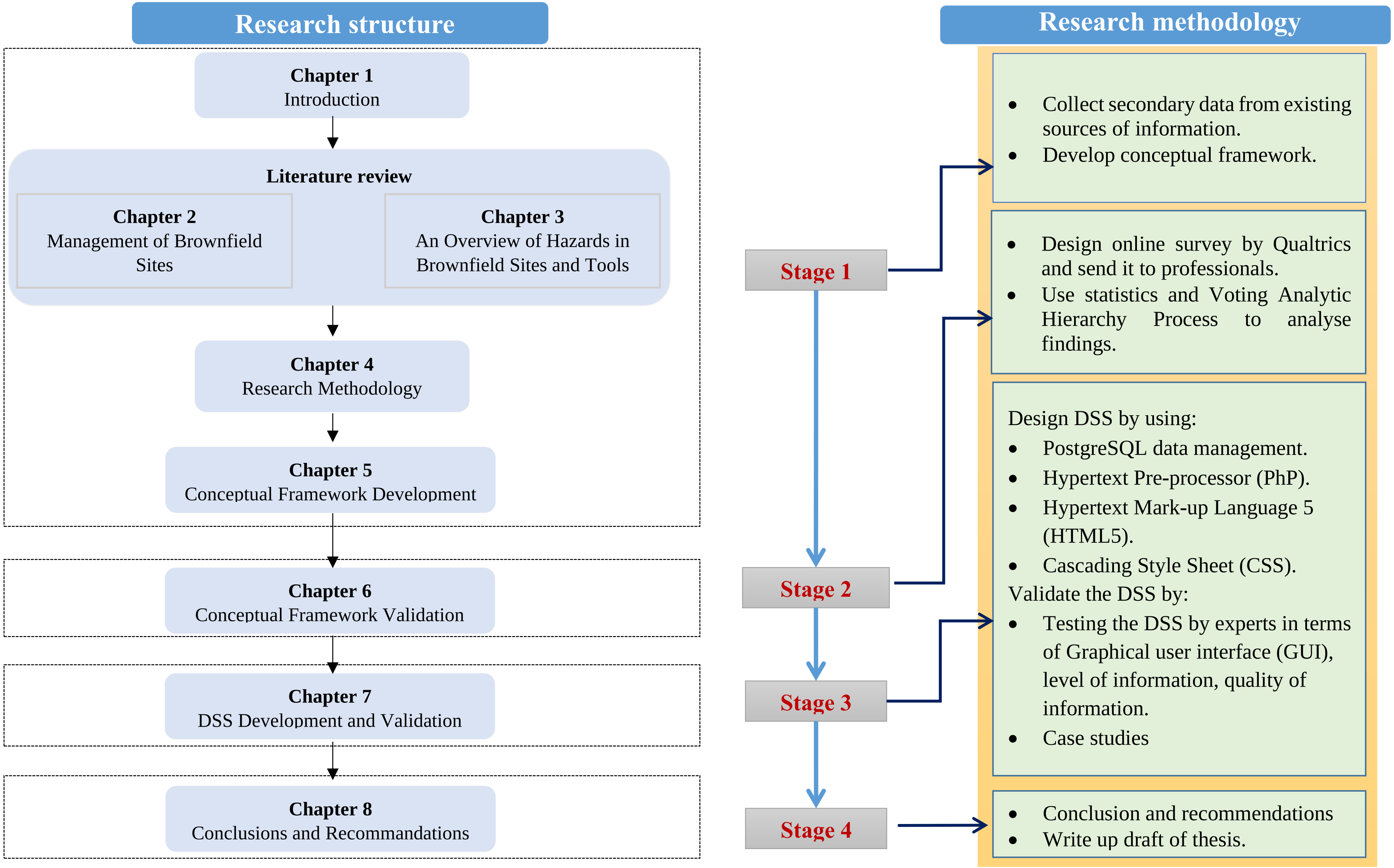

Figure 4:5 Overall research methodology

4.10 Ethical Considerations for the Research

Research ethics is a group of instructions controlling the way any research is conducted. Therefore, ethical considerations are known as one of the most substantial parts of research due to its ability to protect the integrity of research and ethical issues such as the dignity, privacy, and confidentiality of the participants.

This research was designed and conducted according to the research ethical guidelines of the University of the West of England (UWE), Bristol. The ethical form was submitted for approval by the Faculty of Environment and Technology (FET) ethics committee before data collection began. Ethical approval was sought before the recruitment of experts and the collection of data began. The Ethics Form covered the following issues:

- Aims, objectives of and background to the research.
- Research methodology to be used.
- Selection of participants and vulnerable groups.
- Sample size and recruitment strategy of participants.
- Arrangements for obtaining informed consent.
- Information Sheets.
- Arrangements for participants to withdraw from the study.
- Arrangements for maintaining anonymity, confidentiality and personal data.
- Risk and risk management – risks faced by participants.
- Risk and risk management – potential risks to researchers.
- Other ethical issues.

Before the submission of the application, it was signed by one of the research team supervisors as required. Also, a copy of the questionnaire and invitation letter was sent along with ethical application form to UWE’s Research Ethics Committees. Full ethic approval has been given before the survey began. However, per the participant information sheet provided in Appendix B research participants were fully informed about the background, purpose and objectives of the research. Consent forms were also used to solicit participants consent and willingness to participate in the research, including the right to withdraw at any stage of the survey.

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4.11 Chapter Summary

The success of any research is significantly influenced by the way research designed, methods, and techniques adopted to collect data. This chapter explored the research methodology, which justifies the choice of strategy and methods researchers use to conduct their studies. The proposed methodology and design for this study have been presented and discussed. These include research philosophy, research approach, methodology choice, research strategy time horizons and research techniques and procedures.

After selecting the appropriate research methodology, the reliability of the proposed framework will first be examined through a pilot study before embarking on collecting the target data. The methodology process to achieve the aim of this study includes four-stage process, which consists of both quantitative and qualitative methods. Mixed methods are used to provide both breadth and depth in collecting, analysing and understanding the data to create the DSS tool. Stage one involves the creation of a conceptual framework using existing literature to guide the development of the DSS tool. Stage two uses a questionnaire to subject experts validate or sign-off the literature findings. Stage three the development of the DSS tool. Finally, Stage four uses a questionnaire to professionals and case studies to complete the approval of the DSS tool. The next chapter will present the process of developing the conceptual framework that ultimately aims to create a web-based decision support system (DSS) to assist assessors in foreseeing the hazards associated with brownfield sites at early stage.

5. CHAPTER 5: CONCEPTUAL FRAMEWORK DEVELOPMENT

5.1 Introduction

The aim of this chapter is to propose a conceptual framework that provides guidance and structure to future developments and applications in the development of decision support systems for preliminary risk assessment of brownfield sites. The conceptual framework components and their interrelationship could pave the way to a useful approach to guide and stimulate research and theory building in this field, as well as testable relationships between the components and variables of the framework.

This chapter is composed of several sections where Section 5.2 discusses the importance of developing the conceptual framework, Section 5.3 examines research paradigms that have been proposed in this field. It analyses key research avenues considered in these studies and assesses their implication for the study of risk assessment of brownfield sites. Section 5.4 presents the development process of the framework. Section 5.5 describes the proposed conceptual framework, which is designed to draw together previous research and to provide a basis for clarifying the salient research issues. While Section 5.6 summarises the chapter

5.2 Importance of Developing a Framework

Yin (2009) outlined the importance of conceptualising the phenomenon under examination or pre-establishing an initial theory to start data collection. By conceptualising the phenomenon, the researcher can illustrate the main concepts about the study, how the concepts are interrelated and the circumstances within which the concepts and interrelationships are true (Yin, 2017). If research aims to explain a planned or current relationship, the approach could be principally defined by two key concepts; namely, the model and the framework. A framework represents the researcher's synthesis of the literature on explaining a phenomenon (Regoniel, 2015). Three types of the framework are introduced by Eisenhardt (1991), namely 'theoretical', 'practical' and 'conceptual'. Imenda (2014) defined a theoretical framework as the theory that the researcher chooses to guide him in his research. Therefore, a theoretical framework is applying a theory, explaining events, or shedding light on a phenomenon or research study. Whereas, Eisenhardt (1991) defines practical framework as directs the research in *'what works in the experience or exercise of doing something by those directly involved in it.'* A conceptual framework was defined by Neta *et al (*2015) as a structure intended to support and guide researchers for the building of a theory of a research study, to allow researchers to intellectually transition from simply description a phenomenon to generalizing about different aspects of that phenomenon.

The framework is the structure that supports a theory of research study, while the model explores the specific methodology (Abend, 2008). It maps out the possible courses of action of the study given researcher point of view and his observations on the subject of research (Yin, 2017). It is also the presentation in schematic form, often in a simplified way, of a phenomenon or an aspect of a phenomenon (Dakhil, 2017).

This research adopted a conceptual framework for preliminary assessment of brownfield sites, based on the following reasons:

1. The conceptual framework is generic enough to be applied for assessing different types of brownfield sites.
2. The ability of the conceptual framework to offer advice to all levels of professionals involved in the investigation ranging from graduate engineers to senior consultants.
3. The conceptual framework will be designed to help to structure approach to the assessment of brownfield sites.

4. Collecting all information and making them accessible through a single port allows the user to quickly compare datasets. Therefore, the conceptual framework will help to address potential hazards associated with brownfield sites in one platform.

5.3 Paradigms for the Study of Preliminary Risk Assessment of Brownfield Sites

The field of risk assessment of brownfield sites has been characterised by a lack of an established conceptual framework that involves the potential presence of a hazardous substance, pollutant, or contaminant. Laidler, Bryce and Wilbourn (2002) demonstrate that the absence of clear and robust guidance has contributed to a reluctance of governments to develop brownfield sites. In addition, Searl (2012) mentioned that the uncertainty underlying preliminary risk assessment of brownfield site affect stakeholders' decisions. Therefore, the decision to redevelop the brownfield site may be influenced by the fact that the condition of the site is unknown, and the very real possibility of unforeseen hazards. The gap in our knowledge has persisted. Consequently, a strong need for a holistic and comprehensive framework helps assessors identify hazards in brownfield sites, enabling them to gain an informative and fast opinion on any potential liabilities or risks related to the site suitability for development. This chapter aims to bridge this gap and provide a conceptual framework to give a theoretical foundation to the study of preliminary assessment of hazards associated with brownfield sites' redevelopment.

5.3.1 Main Issues in Identification of Hazards in Brownfield Sites

Section 2.4.4 outlined that the starting point of any risk assessment process is hazard identification showing the complex relationships of sources, pathways and receptors (Nathanail. 2007a). Among the challenges are the uncertainties due to the inability to identify hazard source with confidence, particularly for stakeholders with limited knowledge for such sites.

Pathway identifies how hazards were released from the source into the environment, namely pre-exposure (Butt *et al.*, 2016). The pre-exposure is mainly subjected to investigate the impact of site conditions, including site geology, hydrology, and topography on contaminants' fate and transport. Nathanail et al. (2007b) illustrated the impact of the ground's geology on the mobility and potentially toxicity of pollutants, whereas the fate and transport of contaminants is a function of their properties (solubility, volatilization, etc.) and the properties of the ground they are in (clay content, pH, organic matter content, etc.).

Therefore, fata and transport approaches need considerable volumes of data and a large amount of work to set up, which increase the cost of investigation and time-consuming in case of management of thousands of contaminated sites.

Risks posed to receptor (human health) has usually the dominant issue in redeveloping brownfield sites. However, for the contaminant to pose a risk, a human receptor must be present, and a reasonable pathway by which the contaminant could be transferred to the person present on the site and the occupiers could be the receptor most exposed to many of hazards. One of the key challenges to assess the human exposure to contaminants is the uncertainties associated with the interpretation of toxicological information that is likely to continue unless the development of comprehensive and easy tools enables the assessors to reduce their uncertainty and boost their confidence in making decisions. For example, a developer may decide to use a remediation option that will bring a standard higher than is strictly necessary to protect human health. This implies that “over remediation” leading to high cost for developers.

Addressing the above challenges is mainly based on the determination of the required information to identify the pollutant linkage components. Despite the proliferation of this line of research, only a limited number of studies attempted to develop a theory that establishes the necessary information to establish pollutant linkage model.

Consequently, advocate the following criteria for identifying hazards can benefit the planning process, coordinated between relevant stakeholders and reduce uncertainty in the decision-making of brownfield site redevelopers:

1. Less time consuming, i.e. less time and efforts to identify and assess hazards.
2. Costly, i.e. reduce expense for preliminary assessment.
3. Simplicity, i.e. being easy to do and understand.
4. Relevant, i.e. suitable to the purpose of the problem being considered.
5. Accurate, i.e. enough information should be made available for the decision.
6. Right information, i.e. only the appropriate level of details should be included in accordance with the decision-making context.
7. Comprehensible, i.e. the content of the preliminary assessment should be understandable to the layperson, including the owner of land and people effected by the decisions.

5.4 Conceptual Framework Development

The framework development started from an idea based on a literature review that there is a strong need for a framework that will enable assessors to conduct a preliminary risk assessment. To establish the framework for this study it is essential to identify preliminary information needed for initial evaluation of brownfields sites. The pollutant linkage concept can serve as a basis in this research to determine the information required of preliminary assessment of brownfield sites.

The development of the proposed conceptual framework consists of three main steps as follows:

- Identify key information for preliminary assessment of brownfield sites (literature).
- Establish the relationship between the key information and pollutant linkage model (Survey).
- Identify potential hazards for each information (Literature).
- Prioritise the identified hazards in terms of their likelihood of occurrence (Survey)

Accordingly, this Section illustrates the inclusion of key areas elicited from literature to establish the constituent parts (i.e. main concepts and their interrelationships) as presented in Figure *5:1*, thereby developing the conceptual framework of this study.

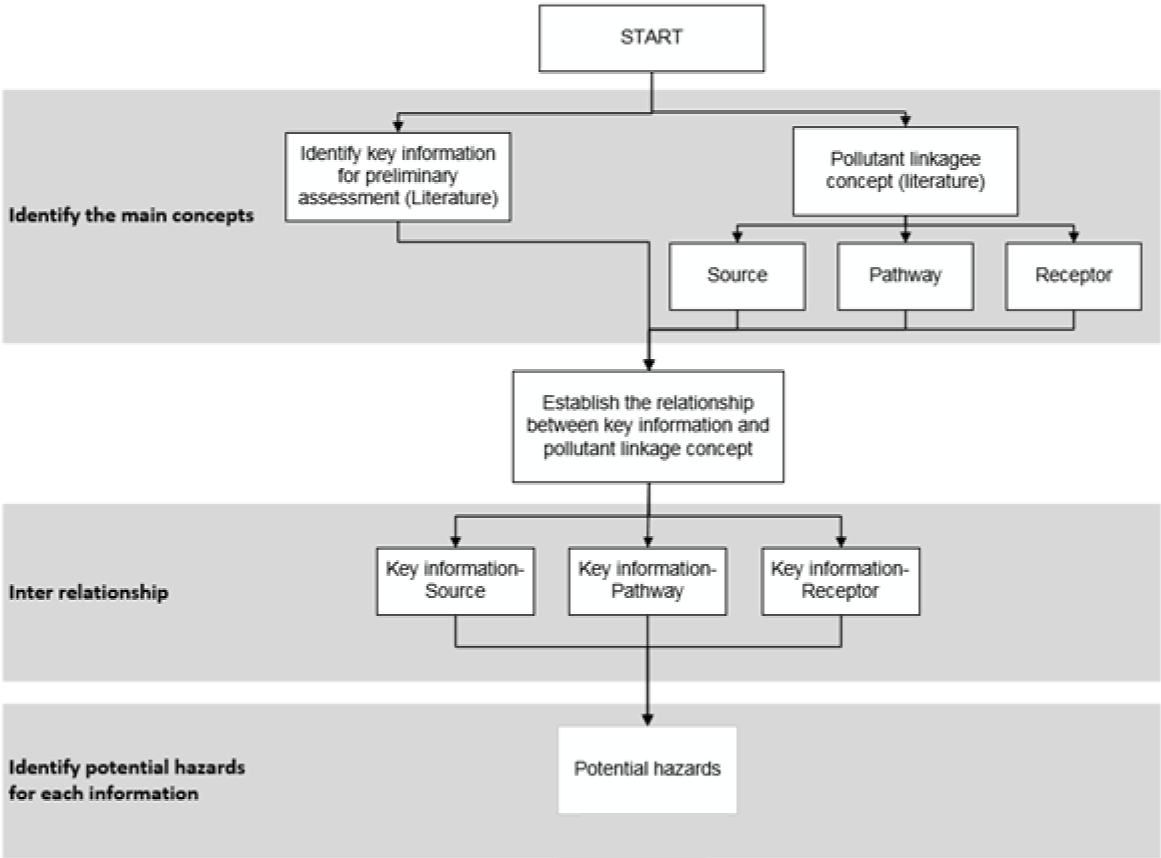

Figure 5:1 Development of the conceptual framework

5.4.1 Information Needs for Preliminary Risk Assessment

To establish the critical information for preliminary information, it was decided to screen the literature. This review was conducted on academic databases and grey literature. The academic database includes Scopus, American Society of Civil Engineers (ASCE) and other leading search facilities. While, grey literature includes government reports, technical reports etc. The research keywords were a combination of "Preliminary" "Hazard assessment", " Hazard identification", "Contaminated sites", "Brownfield sites", "Site investigation", "Site appraisal" and "Site report". They were selected for their comprehensive coverage on the subjects of preliminary assessment of brownfield sites.

After removing the duplicates there were subsequent exclusion rounds by reading the titles, then the abstract and finally the full articles. Following steps involved the removal of irrelevant articles, they were identified and screened based on the following eligibility criteria: (i) irrelevant literature that does not concern preliminary assessment and brownfield sites, (ii) lack of adequate quality. The review findings are presented in Table *5.1*.

Table 5.1 Information needs for preliminary risk assessment

Reference	**Site history**	**Surrounding areas**	**Buildings and other structures**	**Underground services**	**Storage of materials and old tanks**	**Site geology**	**Previous mining activities**	**Presence of radon**	**Invasive species**	**Made ground**	**Site hydrogeology/hydrology**	**Site topography**	**Receptors**
(New Jersey Department of Environmental Protection (NJDEP), 2019)	✓	✓	✓	✓	✓	✓					✓		
(Nikolaidis, 2018)	✓					✓					✓		
(Department of environmental conservation, 2017)	✓	✓	✓		✓						✓	✓	
(Suthersan *et al.*, 2016)	✓					✓					✓		
(Nathanail, Bardos and Nathanail, 2011)	✓	✓	✓	✓	✓	✓					✓		
(Özgen, 2009)	✓					✓					✓		✓
(Environment Agency, 2008)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
(Department of Toxic Substances Control (DTSC), 2008)	✓	✓				✓					✓	✓	✓
(Martin and Toll, 2006)	✓	✓		✓		✓					✓	✓	✓
(DEFRA; Environmental Agency, 2004)	✓	✓	✓	✓	✓	✓						✓	
(Regens *et al.*, 2002)	✓	✓				✓					✓	✓	✓
(McMahon *et al.*, 2001)	✓					✓					✓		✓

Arguably, the environment agency (2008) provides the most detailed information to undertake a preliminary risk assessment, which is adopted in this research study. it can be noticed that this information is fundamental to determine the pollution linkage. After determining the main concepts of the conceptual framework, the next section will detail the interrelationship between the necessary information for preliminary information and the component of pollutant linkage model.

5.4.2 Relationship between the Key Information and Pollutant Linkage Model

As the second step of developing the conceptual framework, this section establishes the relationship between the key information (Section 5.4.1) and pollutant linkage model (Section 2.4.3) as illustrated in Figure 5:*2*.

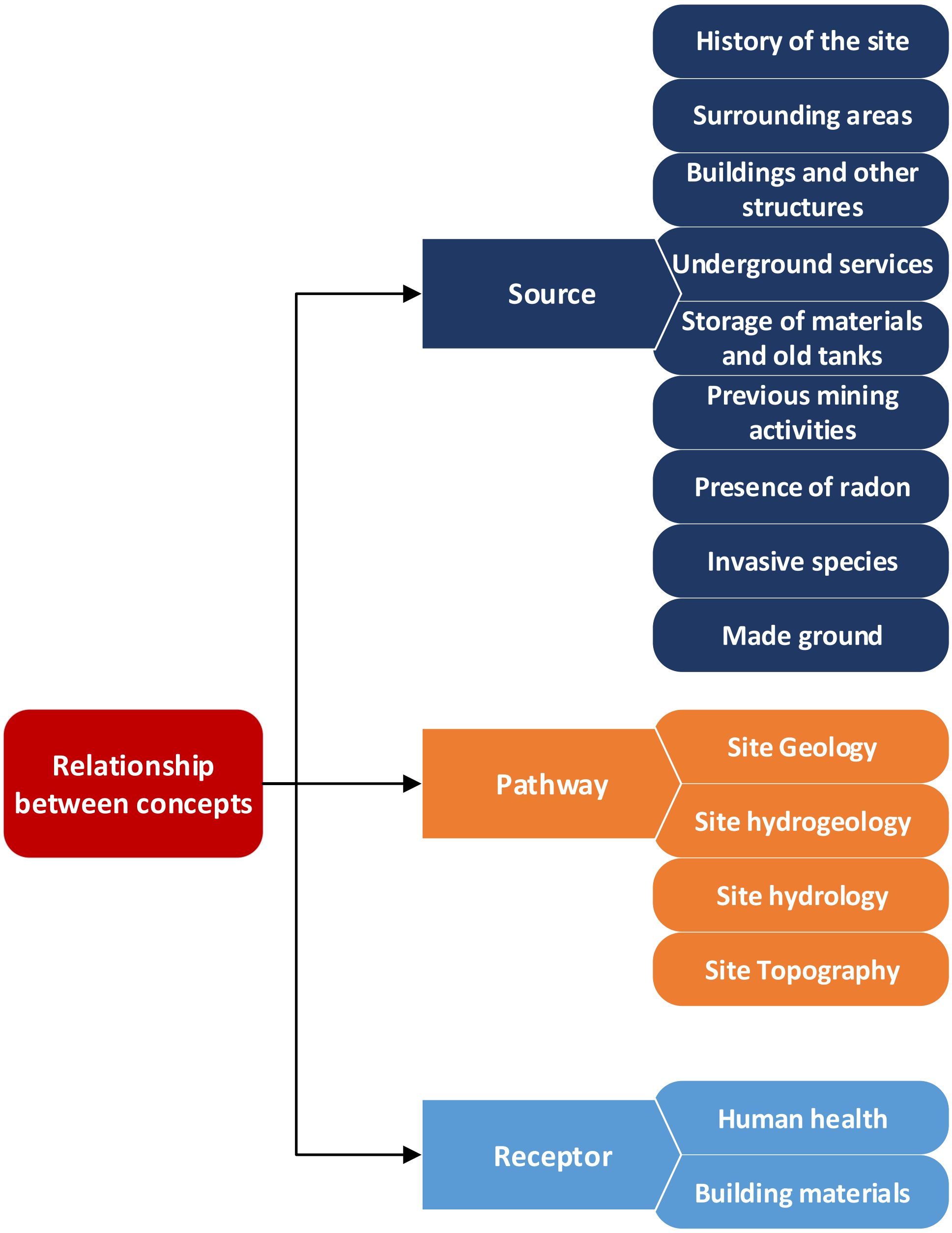

Figure 5:2 Relationship establishment between pollutant linkage concept and key information for preliminary assessment

5.4.2.1 Key information to identify hazards source

The determination of hazards within preliminary assessment of brownfield sites involves identifying possible sources. The sources of hazards were classified in chapter 2 into:

1. Physical hazards (Section 3.2.1)
2. Chemical hazards (Section 3.2.2)
3. Biological hazards (Section 3.2.3)

The following section will discuss in details the essential information to identify the potential source of hazards in brownfield sites.

5.4.2.1.1 Site history

Site history generally provides a good indication of potential sources and types of hazards likely to be found on site due to the previous use of the site. Section 2.3 discussed the source of hazards in brownfields sites and shows that previous activities left a wide range of physical hazards, chemical hazards and biological hazards. Identifying such hazards is reasonably simple, as manufacturing processes, materials and waste of past industries are well documented. However, a full series of forty-eight industrial profiles that give rise to brownfield sites problems have been identified by the Environment Agency (2008). To illustrate how predict the potential hazards based on site history, an example is shown in Table 5.2.

Table 5.2 Example of potential hazards related to the site history information

Site history: Airport	Code	Potential hazards	References
Physical hazards	PH1	• Underground pipeline • Hangars and ancillary workshops • Building and pipework • Waste disposal areas • Electrical transformer	(Departement of the Environment, 1995; Environment Agency, 2008)
Chemical contaminants	PH2	• Metals and their compounds: Arsenic, Zinc, Barium, Cadmium, Copper, Fer, Chromium, Lead, Nickel, Mercury. • Organic and inorganic: Chlorinated Solvents, Phenol, PCbs, PAHs, Oil/fuel hydrocarbons, Dioxins and furans, Asbestos, Acid Aromatic hydrocarbons	
Biological contaminants	PH3	• No evidence of Biological hazards	

5.4.2.1.2 Surrounding area

In areas where the surrounding sites are known by historical industrial activities, it can be considered as a source of contamination, because the behaviour of the site containing contamination is the long-term migration of the contaminants itself to potential receptors. In order to have an adequate assessment, the assessor is required to determine the neighbouring land use type on the northerner, southern, western and eastern boundaries. Such information is extremely useful to determine whether there is a potential for contamination to be present which could affect current or future uses of a site and potentially pose a risk to occupiers, neighbours or the wider environment (World Health Organization, 2013). Table 5.3 illustrates the potential hazards related to surrounding areas.

Table 5.3 Potential hazards related to surrounding area information

Surrounding area	Code	Potential hazards	References
Industrial/Commercial	PH4	Pollutants migration from industrial/commercial site to adjacent sites (e.g. in the period of heavy rainfall or snowmelt).	(Environment Agency, 2008; Bougherira *et al.*, 2014)
	PH5	Excavation of the industrial/commercial site may disturb contaminates and release them into watercourse and water supplies which may pose a risk to neighbourhood residents.	(Leach and Goodger, 1991; Fent, 2003; Billington, 2007a; Watts and Charles, 2015)
Residential	PH6	Pollutants migration from brownfield sites to neighbour residential (e.g. in the period of heavy rainfall or snowmelt).	(Leach and Goodger, 1991; Fent, 2003; Billington, 2007a)
	PH7	Excavation of brownfield site may disturb contaminates and releasing them into watercourse and water supplies which may pose a risk to neighbour residential.	(Environment Agency, 2008; Mouri *et al.*, 2014; Cole and Marney, 2012)

5.4.2.1.3 Buildings and other structures

The information related to the presence of buildings and other structures is important because statistics indicate that demolition of old buildings without adequate decommissioning and decontamination remains a worldwide problem although the safety improvement in the construction, it still exposes the high number of workers to a fatal hazard (Ruikar, 2016). Therefore, the information related to buildings and other structures plays a vital role when identifying the source of hazards in brownfield sites, Section 3.2.1 outlines hazards associated with the presence of buildings and other structures. Table 5.4 shows the potential hazards due to the existing of building and other structures in brownfield sites.

Table 5.4 Potential hazards related to buildings and other structures information

Buildings and other structures	Code	Potential hazards	References
Does exist	PH8	Hazards related to demolition activities of existing buildings and other structures.	(Charles *et al.*, 2002; Skinner, Charles and Tedd, 2005; HSE, 2006)
	PH9	Old foundations failure due to chemical soil attack that leads to foundations degradation.	(Charles *et al.*, 2002; Skinner, Charles and Tedd, 2005; Hertlein and Walton, 2007)
	PH10	Hazards from sharp objects (e.g. glass, metallic objects).	(Barry, 1991)
Does not exist	N/A	N/A	N/A

5.4.2.1.4 Underground services

This information is necessary because most of the brownfield sites already have underground services. This presents potential physical obstructions to redevelopment which, if not foreseen and planned for, can have a major significance when discovered during construction. Additional chemical hazards arise if damage occurs to gas pipes when the work is carried out, or subsequently. This damage may cause leaks that lead to site contamination, fire or explosion (Section 3.2.1). The potential hazards associated with underground services are presented in Table *5.5*.

Table 5.5 Potential hazards related to underground services

Underground services	Code	Potential hazards	References
water pipes and sewers	PH11	Damage to water pipes and sewers may cause floods.	(Mi, 2007; Noh *et al.*, 2016)
	PH12	Contaminants in the ground can pose a risk to potable water supply by permeating plastic water.	(Hill, Slade and Steeds, 2001; LeChevallier *et al.*, 2003)
	PH13	Leaks of water from underground pipes can affect adjacent services and reduce support for other structures.	(Charles *et al.*, 2002; Charles, 2005)
	PH14	Damage to a sewer poses risks to the health of workers from exposure to raw sewage.	(HSE, 2006, 2013a)
Gas pipes	PH15	Risk of fire and explosion due to flammable gases.	(HSE, 2006; Shin *et al.*, 2018)
	PH16	Risk of leakage due to damage of connections.	(HSE, 2006; Best, 2007; Department for

			Communities and Local Government, 2008)
	PH17	Risk of asphyxiation due to inert gases such as nitrogen and argon.	(HSE, 2006; Peterson, 2015)
	PH18	Risk of poisoning due to toxic gases.	(Leach and Goodger, 1991; Ong and Teugels, 2016)
	PH19	Risk of release contents due to elevated pressure.	(British Standard Institution, 2004a, 2004b)
Electricity cables	PH20	Explosive, fire or flames that may result when a live cable is penetrated by a sharp object.	(HSE, 2006; Wilkinson and David, 2009; HSE, 2013b)
	PH21	Damage of electricity cables may pose a risk to near services.	(HSE, 2006, 2013b)
	PH22	Hazards of electrical cables to burn hands, face and body.	(Timmons, 1981; HSE, 2013b)
	PH23	Cables which have been damaged but left unreported and unrepaired, or which have deteriorated with age.	(HSE, 2006, 2013b, 2013a)
Telecommunication cables	PH24	The possibility of flammable and toxic gases migration through telecommunication cables.	(HSE, 2013a, 2017)

5.4.2.1.5 Storage of materials and old tanks

The information related to storage materials and tanks raise concerns about chemicals and other liquid raw materials stored in tanks (Section 3.2.1), all of which may leak or result in contamination through spills and leakage. Also, the ground instability hazards related to removing tanks and underground storages. The potential hazards associated with storage and tanks are presented in Table *5.6*.

Table 5.6 Potential hazards associated with storage and tanks

Storage and tanks	Code	Potential hazards	References
Does exist	PH25	Chemicals and other liquid raw materials stored in tanks and soils.	(Barry, 1991; Leach and Goodger, 1991; Watts and Charles, 2015)
	PH26	Ground instability related to removing tanks and underground storages	(Barry, 1991; Leach and Goodger, 1991; Charles, 2005; Watts and Charles, 2015)
Does not exist	N/A	N/A	N/A

5.4.2.1.6 Previous mining activities

The information related to previous mining activities is vital to identify hazards such as subsidence and collapsing of voids due to the presence of large voids at shallow depth (outlined in Section 3.2.1.1.3). The potential hazards associated with previous mining activities are presented in Table *5.7*.

Table 5.7 Potential hazards associated with previous mining activities

Previous mining activities	Code	Potential hazards	Reference
Yes exist	PH27	Pollution resulting from mine water and contaminated shaft fill.	(Lee, Chon and Kim, 2005; Li and Ji, 2017; Nikolaidis, 2018)
	PH 28	Subsidence and collapsing of voids due to the presence of large holes at shallow depth.	(Charles, 2005; Kelm and Wylie, 2007; Watts and Charles, 2015)
	PH 29	Emission of noxious or asphyxiating mine gases.	(Ramirez-andreotta *et al.*, 2013; Argyll Environmental Ltd, 2018; Kim *et al.*, 2019)
	PH 30	Spontaneous combustion of coal by exposure to atmospheric conditions.	(Charles, 2005; Li *et al.*, 2009; Qi *et al.*, 2019)
Not exist	N/A	N/A	N/A

5.4.2.1.7 Presence of radon

This information can be used to identify the source of hazards in brownfield (Section 3.2.2.2). However, the early identification of radon will help in adopting the right mitigation measures to reduce health hazards. According to the United States Environmental Protection Agency (EPA, 2019) there is no danger to the public out of doors, although there may be a potential increase in exposure of occupants in residences over ash–disposal sites from increased radiation flux out of the ground. This is not of great radiological significance, and no action is considered necessary in existing residences. For proposed new buildings, simple precautions may usefully be considered at the planning stage to keep radiation levels (from accumulating radon gas) as low as reasonably achievable (Leach and Goodger, 1991). Table *5.8* shows the potential hazards associated with the presence of radon gas in brownfield sites.

Table 5.8 Potential hazards associated with the presence of radon

Presence of radon	Code	Potential hazards	Reference
Yes exist	PH31	Radon may migrate into buildings, which may cause lung cancer, particularly for smokers and ex-smokers.	(Hampson *et al.*, 2000; Tracy *et al.*, 2006; Zielinski *et al.*, 2006)
Not exist	N/A	N/A	N/A

5.4.2.1.8 Invasive species

This information is important because brownfield sites often affected by invasive species. An invasive species is an animal or plant that harms an environment after being introduced to humans. In some places, invasive species have changed the natural world beyond recognition (Clavero and García-Berthou, 2005). Section 3.2.3.2 outlined the potential hazards caused by invasive animals and plants for human health and the safety of buildings. However, Mazza *et al*. (2013) indicate that invasive plants species are similar to pollutants and maybe even more dangerous than chemicals in the invaded areas. They reproduce and spread autonomously and, consequently, even if the source of introductions ceases its activity, their adverse effects continue and often increase over time. Additionally, invasive animals' species pose a risk by transmitting viruses to human health in brownfield sites. Table *5.9* shows the potential hazards associated with invasive species in brownfield sites.

Table 5.9 Potential hazards associated with invasive species

Invasive species	Code	Potential hazards	Reference
Invasive plants	PH32	Aggressive plant may cause damage to the structure of a building such as drains, services, and walls.	(Maerz, Blossey and Nuzzo, 2005; Payne *et al.*, 2012)
	PH33	Invasive plants may cause immense landslides and soil erosion.	(Walker, Velázquez and Shiels, 2009)
	PH34	Health issues due to contact (e.g. dermal contact, swallowing) with invasive plants.	(Batish *et al.*, 2004; Culliney, 2005; D'hondt *et al.*, 2015)
Invasive animals	PH35	Transmission of viruses to humans.	(Crowl *et al.*, 2008)

5.4.2.1.9 Made ground

Made ground provides a good indicator of the hazards related to such as type of ground. The review of this study shows that the potential hazards related to the made ground are ground movement hazards due to chemical reactions (Section 3.2.1.1), substance chemical (Section 3.2.2) and gas generated from biodegradable (Section 3.2.2.2). Table 5.10 shows the potential hazards associated with the made ground.

Table 5.10 Potential hazards associated with made ground information

Made ground	Code	Potential hazards	References
Does exist	PH36	Failure of construction materials, because of their vulnerability to aggressive ground conditions.	(Baker, 1980; Bartarya, 2013a; Seeley and Winfield, 2015)
	PH37	Hazards for buildings and occupants, arising from combustion.	(Richards, 1998; Blight, 2009; Kim *et al.*, 2013)
	PH38	The migration of contaminants from landfill site over time increases the possibility of groundwater to be contaminated.	(Broholm *et al.*, 1998; Jensen, Ledin and Christensen, 1999; Smith, 2005; Augustsson *et al.*, 2016)
	PH39	Damage to buildings due to volume changes in fill caused by physical, chemical or biological reactions.	(Charles and Skinner, 2004; Skinner, Charles and Tedd, 2005; Lucian, 2006; Watts and Charles, 2015)
	PH40	The generation of methane and carbon dioxide with volatile organic compounds. (VOC) as result to microbial activity	(Bouazza and Kavajanzian, 2001; Jonidi jafari and Talaiekhozani, 2010; Maheshwari, Gupta and Das, 2015; Talaiekhozani *et al.*, 2018)
Does not exist		N/A	N/A

5.4.2.2 Key information to identify the pathway

Pathways identification with the initial assessment of brownfield sites involves addressing potential routes for migration of contaminants within the site or off-site. On consultation of the vital information, three main factors were identified as follows:

- site geology;
- site hydrogeology/ hydrology and;
- site topography.

5.4.2.2.1 Site geology

The geology information presents data due to the permeability of the soil and its thickness. These data allow the assessors to understand the site's geology and enable judgments to be made regarding the possible movement of contamination through the various types of site geology. However, studies (Briish Standard, 1990; Sibley *et al.*, 2002; Hayashi and Rosenberry, 2002) indicated that underlying geology could provide a significant pathway for leachate into groundwater, nearby surface water and adjacent sites (outlined in Section 2.4.3.2). The site-specific geological settings influence the fate and transport of potential contaminants on and in the vicinity of a site, and the possible exposure pathways to human health and environmental receptors. The presence of low permeability ground (clay, membrane, concrete slabs, etc.) may cause an increased pressure, resulting in greater migration of contaminants (Carter, 1983; Kumar *et al.*, 2006; Siracusa *et al.*, 2007). Table *5.11* illustrates the potential hazards associated with the permeability of the soil.

Table 5.11 Potential hazards associated with soil permeability

Soil types	Code	Drainage conditions	Permeability (m/s)	Potential hazards	References
Homogeneous clay	PH41	Practically impermeable	10^{-11}–10^{-9}	Because of the impermeable features of homogeneous clay, the migration of the contaminants is practically excluded. which creates a persistent, secondary source of contamination that is difficult to remediate.	(Carter, 1983; Miller *et al.*, 2011)
Silts, fine sands, clay	PH42	Poor	10^{-9}–10^{-7}	Because of the poor permeability, the soil underlying the site slows down the migration of contaminants, which creates a persistent, secondary source of contamination that is difficult to remediate.	(Carter, 1983; Westcott, Smith and Lean, 2003; Nathanail, Bardos and Nathanail, 2011)
Clean sands, sand and gravel mixture	PH43	Good	10^{-5}–10^{-3}	The soil underlying the site accelerates the migration of contaminants for groundwater, nearby surface water and adjacent sites.	
Clean gravel	PH44	Very good	10^{-3}–1	The soil underlying the site accelerates the	

				migration of contaminants for groundwater, nearby surface water and adjacent sites.	

The thickness parameter also plays an essential role when assessing contaminants pathway movement, as the thicker the layer the longer take the contaminants to move through it, which increase the risk of pollutants stagnate while decreasing the risk of contaminants movement to adjacent sites (Briish Standard, 1990). Table 5.12*Table 5.4* presents the potential hazards associated with the thickness of the soil.

Table 5.12 Potential hazards associated with soil thickness

Soil thickness	Code	Thickness	Potential hazards	References
Very thickly	PH45	>2m	A very thin layer accelerates the migration of contaminants for groundwater, nearby surface water and adjacent sites.	(Carter, 1983; Martin and Toll, 2006)
Tickly	PH46	600mm–2m	A tickly layer accelerates the migration of contaminants for groundwater, nearby surface water and adjacent sites.	
Medium	PH47	200mm–600mm	Medium layer the soil underlying the site slows down the migration of contaminants, which creates a persistent, secondary source of contamination that is difficult to remediate	
Very thinly	PH48	20mm–60mm	Very thinly layer the soil underlying the site slows down the migration of contaminants, which creates a persistent, secondary source of contamination that is difficult to remediate	

5.4.2.2.2 Site hydrogeology/ hydrology

The site-specific hydrogeological and hydrological settings play a critical role when assessing possible pathway because it influences the movement of potential contaminants on and in the vicinity of a site, and the potential exposure pathways to human health and environmental receptors (outlined in section 2.4.3.2). The presence of groundwater and/or surface water helps contaminants' movement, therefore increasing the risk. Otherwise, it is essential to bring the attention of the reader that groundwater, surface water is considered in some tools like receptors of the contaminants but may also act as pathways via consumption of water, direct contact with receptors. This research study adopts groundwater and surface water as a pathway of pollutants. The potential hazards related to site hydrogeology/ hydrology are presented in Table *5.13*.

Table 5.13 Potential hazards associated with site hydrogeology/hydrology

Hydrogeology/hydrology	Code	Potential hazards	References
Presence of groundwater	PH49	The presence of groundwater increases contaminants' movement to adjacent sites and/or surface water systems, which raise risks to human health and aggressive attack to building materials.	(Kawai, Yamaji and Shinmi, 2005; Bartarya, 2013b; Ahmad *et al.*, 2013; Hadigheh, Gravina and Smith, 2017; Naveen, Sumalatha and Malik, 2018)
Presence of surface water	PH50	The presence of surface water increases contaminants' movement to adjacent sites and/or groundwater, which raises risks to human health and aggressive attack to building materials.	
Flooding zone	PH51	The upwards movement of contaminants in groundwater following flooding or excessive rainfall.	(Environment Agency, 2008)

5.4.2.2.3 Site topography

The information related to the site's topography plays an essential role in identifying the direction of the contaminant pathway. Topography of the site is the simplest way to explain the transport of pollutants. For example, topography steep to the river can give an indication of both surface water runoff direction but also local groundwater flow. However, the transport of pollutants can be explained by Darcy’s Law that relates the hydraulic gradient with the bulk properties of the materials (porosity) (Cachada, Rocha-Santos and Duarte, 2017; Durães *et al.*, 2018). However, the assessors should consider the boundaries of the site, because if the site is in the direction of the steep previous use site, then the hazards of contaminants migration are increased. Otherwise, Environment Agency (2013) considered that managing contaminants on flat sites can be a challenge because it increases infiltration and vertical movement of contaminants (Boulding, 2017). The potential hazards associated with site topography presented in Table 5.14.

Table 5.14 Potential hazards associated with site topography

Site topography	Code	Potential hazards	References
Steep brownfield site	PH52	Spreading of contaminants as result of slope failures.	(Salgado *et al.*, 2013; Boulding, 2017)
	PH53	Migration of contaminants in the direction of the slop.	
Flat brownfield site	PH54	Horizontal sites increase infiltration and vertical movement of accumulated contaminants towards groundwater.	(Gurunadha Rao and Gupta, 2000; Burgos *et al.*, 2008)
	PH55	Horizontal sites reduce contaminants flow which creates a source of contamination that increase environmental pollution.	(Galletti, Verlicchi and Ranieri, 2010)

5.4.2.3 *Key information to identify the receptor*

The identification of the receptor is critical to complete the Source-Pathway-Receptor assessment process. Risk cannot exist unless there is a possible scenario, for that reason if a receptor is not identified, then the other components have no worth. However, on any particular site, a range of possible receptors can include any or all of the following:

- Human health (e.g. site workers, future occupiers, neighbouring occupiers)
- Water environment (e.g. groundwater, surface water)
- Ecosystems (e.g. ambient air, flora and fauna)
- Building materials (e.g. concrete, metals)

On investigating potential receptors, it became clear that some receptors require quantitative data, which may not be available from the preliminary stage. This meant this study eliminates the receptors that are not able to assess. It was concluded that the following receptors: human health, water environment, ecosystems and building materials were unsuitable for this study. Such receptors usually require quantitative data related to contaminants concentration, its amount and the presence of water. Despite that future occupiers also need the mentioned data, a practical risk assessment for such receptors can still be predicted using preliminary risk assessment. In addition, it was also decided that although quantitative data were needed for buildings and services, a simple risk assessment could be performed with the tool.

5.4.2.3.1 Future end-use

In reviewing the future land use, the assessor seeks to identify the types of people using the site, in particular, the critical receptors, who are the most people likely to be exposed or susceptible to the presence of soil contamination (Environmental Agency, 2009). Although most studies consider the potential effect of contaminated land on the general population, children are believed to be the most sensitive category. This is because their body is undergoing developmental changes (e.g. development of the nervous system) and they spend a more significant proportion of their time outdoors, so they are more likely to be exposed to contaminants present in soils. Also, they have more deficient concept of hygiene than adults, and often adopt behaviours that increase their exposure (e.g. crawling activities, geophagia). Otherwise, SR3 report developed by (Environmental Agency, 2009) describes three future land-use scenarios: residential with/out homegrown produce, allotment gardens and commercial. Table 5.15 presents the potential hazards associated with the future end-user

Table 5.15 Potential hazards associated with future end-use scenarios (derived from Environment Agency, 2009b; Nathanail, Bardos and Nathanail, 2011)

Future end-use	Code	Critical receptor	Exposure pathways
Residential with consumption of homegrown produce	PH56	Female child (0 to <6 years); Gardeners	• Direct ingestion of soil • Ingestion of homegrown produce • Ingestion of soil attached to homegrown • Inhalation of indoor and outdoor dust • Inhalation of indoor and outdoor vapours • Dermal contact with soils and dust
Residential without consumption of homegrown produce	PH57	Female child (0 to <6 years)	• Direct ingestion of soil, • Inhalation of indoor and outdoor dust, • Inhalation of indoor and outdoor vapours, • Dermal contact with soils • Dermal contact with dust (Indoors)
Commercial	PH58	Female worker 16 to <65 years	• Direct ingestion of soil • In halation of indoor and outdoor dust • Inhalation of indoor and outdoor vapours • Dermal contact with soils • Dermal contact with dust
Public open space	PH59	Female child 0 to <6 years	• Direct ingestion of soil • Inhalation outdoor of dust, • Inhalation outdoor of vapours, • Dermal contact with soils

5.4.2.3.2 Building materials

Section 3.2.2.3 shows that building materials in brownfield sites are often subjected to aggressive environments that cause them to physical or chemical changes. These changes may result in loss of strength or other changes that will put at risk their structure materials. These materials are concrete, reinforced concrete, steel, masonry and geosynthetics. The potential hazards associated with building materials are presented in Table *5.16*.

Table 5.16 Potential hazards associated with building materials in brownfield sites

Materials		Code	Potential hazards	References
Concrete		PH60	Contaminants contact with concrete cause damage leading to loss of strength, stiffness and cracking.	(Building Research Establishment (BRE), 1991, 2005)
Reinforced concrete		PH61	Reinforced corrosion may happen either of corrosion ions, for example, attack by chlorides, or as a result of a reduction in the PH of concrete through carbonation.	(Asrar *et al.*, 1999; Building Research Establishment (BRE), 2005; Poursaee, 2016)
Asbestos cement		PH62	Asbestos cement is highly durable material, can be considered as strongly resistant to contaminants. Otherwise, certain contaminants such as Sulphate the asbestos cement show less resistant.	(British Standard Institution, 1988; Garvin *et al.*, 1999)
Metal		PH63	Many metals such as cast iron, stainless steel, galvanised and aluminium are used in the substructure. All these metals can deteriorate through the corrosion process.	(Lankes, 1981; Galka and Yates, 1984)
Organic Materials	**Plastic** **Plastic Membranes and Geotextiles** **Plastic pipes**	PH64	Plastics deteriorate by the degradation of their polymeric constituent. Damage of plasticiser and change the physical properties and characteristics of polymeric materials.	(Crathrone *et al.*, 1987; Shimao, 2001)
Masonry	**Clay Brick**	PH65	Although the characteristics of clay bricks to resist to chemical attack, but their permeability will let them at high risk from salt crystallisation.	(Somsiri, Zsembery and Ferguson, 1985; Hansen and Kung, 1988)

5.5 The Conceptual Framework

The increasingly widespread use of brownfield sites in the countries with rich industry past coupled with the complexity of such as site has enhanced the need to develop a conceptual framework that helps to conduct a preliminary risk assessment. This stage allows assessors to identify and assess potential hazards based on pollutant linkage model. Consequently, this present research seeks to bridge this gap and provide a conceptual framework that will answer the challenges facing different stakeholders dealing with brownfield sites to identify and assess potential hazards. The conceptual framework was developed to help professionals conduct a preliminary assessment of brownfield sites, enabling them to gain an informative and fast opinion on any potential liabilities or risks related to the site suitability for development and the acquisition. In this context, the conceptual framework outlines the suitable information that could provide information regarding three elements, including hazard source, pathway and receptors. The proposed conceptual framework is presented in Figure 5:*3*, while its legends are shown in Table 5.17.

Table 5.17 Conceptual framework table legends

Abbreviation	Definition	Abbreviation	Definition
ANI	Animals	PH	Potential hazards
ASC	Asbestos cement	PLA	Plants
BUM	Building materials	POO	Poor permeable
BUS	Buildings and other structures	PRI	Impermeable
C/IN	Commercial/Industrial	PRM	Previous mining activities
COM	Commercial	PRR	Presence of radon
CON	Concrete	RC	Residential with consumption of homegrown produce
ELC	Underground services –Electricity cables	RCO	Reinforced concrete
FLA	Topography–Flat site	RES	Residential without consumption of homegrown produce
FUS	Future end user	RWC	Residential with consumption of homegrown produce
GAP	Underground services –Gas pipes	SOT	Storages of materials and old tanks
GEO	Site Geology	STE	Topography–Steep site
GOO	Good permeability	SUA	Surrounding areas
HIS	Site history	TEC	Underground services –Telecommunication cables
HUH	Human health	THC	Tickly
HYD	Site hydrology	THI	Soil Thickness
INS	Invasive species	TOP	Site topography
MAG	Made ground	UNS	Underground services
MAS	Masonry	VEN	Very thinly
MED	Medium thickness	VER	Very good permeable
MET	Metal	VET	Very thickly
ORM	Organic materials	WAP	Underground services –Water pipes
PER	Soil Permeable		

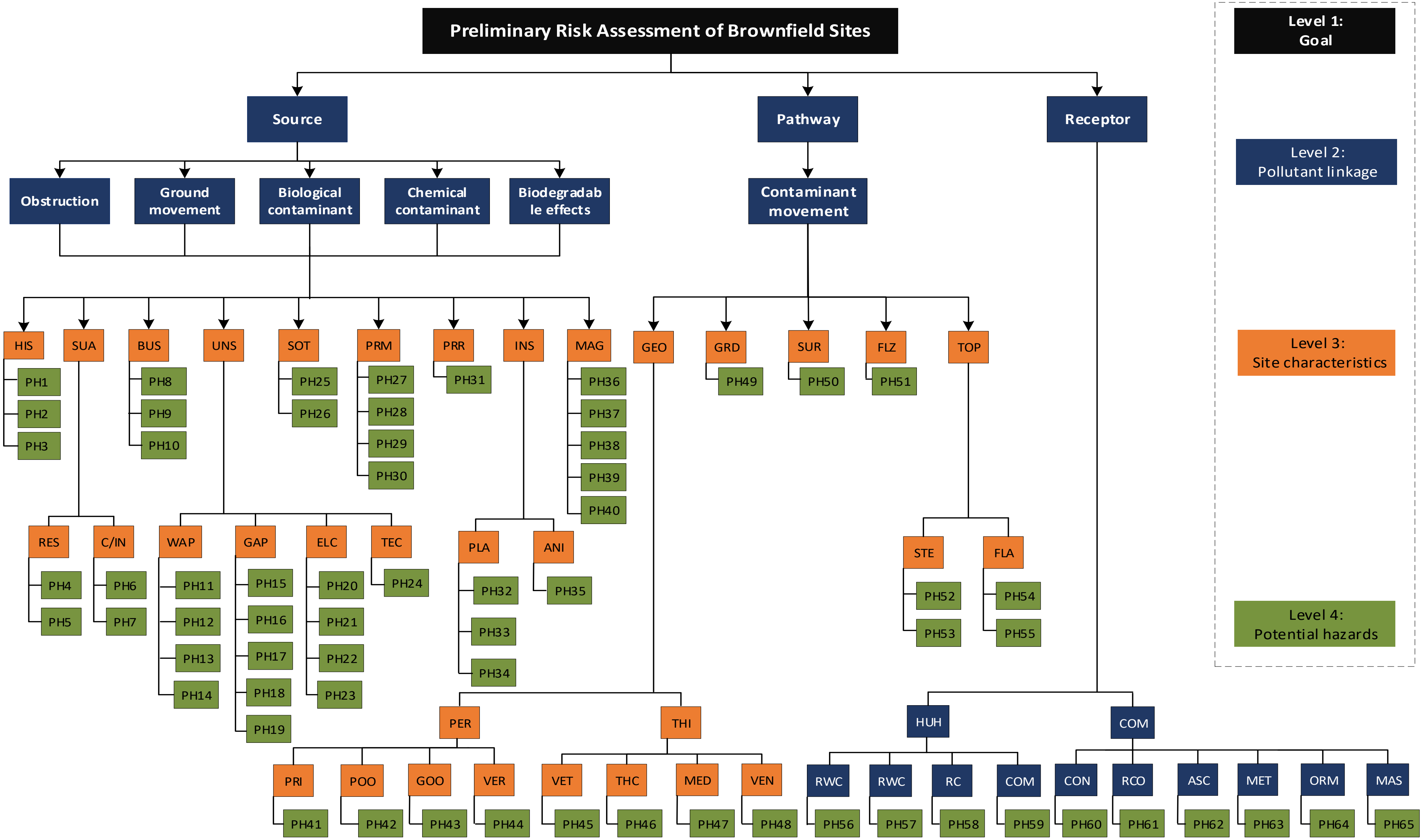

Figure 5:3 Initial conceptual framework for preliminary risk assessment of brownfield sites

The literature reviewed in Chapters 2 and 3 stressed that three key issues need to be explored to conduct a preliminary risk assessment of brownfield sites. Therefore, this conceptual framework was developed based on the following three elements:

- Pollutant linkage model
- Site characteristics
- Potential hazards

5.5.1 Pollutant Linkage Model

The development of the pollutant linkage model (Source-Pathway-Receptor) is based on collecting information as outlined in Section 5.4.2. For this study, the pollutant linkage components are defined as follows:

1. Source: as a result of the review conducted in chapter 2 and chapter 3 the hazards associated with brownfield site have been classified into physical hazards chemical hazards and biological hazards. These categories consist of 6 subcategories in total. They are the physical hazards (obstructions and ground movement), the chemical hazards (contaminated sites, biodegradation of fills and chemical attack to building materials) and biological hazards (pathogenic, micro-organisms and invasive species). These emerge as the main hazards due to brownfield site development
2. Pathway: this research distinguished two parts of contaminants pathway, which are pre-exposure route and exposure. Firstly, the pre-exposure route of contaminants investigated the parameter which may affect the contaminant fate and transport. Section 2.4.3.2 illustrates that site geology, site hydrogeology/hydrology and site topography are essential parameters that effect contaminants transmission. Secondly, contaminants exposure route is defined as a route or means by which a receptor can be exposed to, or affected by, a contaminant. The main exposure pathway which a chemical and biological agent may reach a human are inhalation, ingestion and direct contact.
3. Receptor: brownfield site can contain a wide range of hazards, and there are also very different receptors for these hazards. This research project considers residential, which may be at risk in brownfield and building materials that could be subjected to site condition in future use.

5.5.2 Site Characteristics

Site information is required for conducting preliminary risk assessments. With this information, potential hazards identified, and behaviours can be confidently determined, allowing solutions to be managed. This research conducted a review of academic databases and grey literature to identify the necessary information to develop a comprehensive understanding of the potential hazards associated with brownfield sites. As indicated by review findings, the following information is essential to identify potential hazards:

- Site history provides background information, to monitor the impact of anthropogenic activities or to provide information on site sensitivity. As highlighted in Section 2.3, previous activities of the site rising concerns including physical, chemical and biological hazards.
- Surrounding areas are considered as a source of contamination because of the migration of contaminants to potential receptors. Moreover, it is crucial to determine the neighbouring land use type (commercial, residential, etc.) to identify human receptors.
- Buildings and other structures present physical obstruction hazards, which is essential for identifying concerns such as demolition activities (outlined in Section 3.2.1.2).
- Underground services also present physical obstruction hazards. However, damage to underground services may cause chemical hazards, for instance, contaminants leaks from gas pipes (outlined in Section 3.2.1.2).
- Storage and tanks, raise concerns about chemicals and other liquid raw materials stored in tanks, all of which may leak or result in contamination through spills and leakage. Also, the ground instability related to removing tanks and underground storages as shown in Section 3.2.1.2.
- Previous mining activities is essential to identify physical hazards (i.e. subsidence and the collapse of voids), chemical hazards (i.e. gas emission), physicochemical (expansive reactions of slags) (outlined in Section 3.2.1.1.3).
- Presence of radon is a chemical element that rise concerns to human health (outlined in Section 3.2.2.2)
- Invasive species raises concerns about biological hazards (outlined in Section 3.2.3.2)

- Made ground, indicate physical hazards (ground movement) and chemical hazards (contaminated site and biodegradation of fills) as discussed in Section 3.2.1.1, Section 3.2.2 and Section 3.2.3 respectively.
- Site geology, the transmission of contaminants (pre-exposure) is strongly affected by the geology conditions of the site, including soil permeability and its thickness (outlined in Section 2.4.3.2).
- Site hydrogeology/hydrology, the presence of groundwater or surface water may also play an important in the transmission of contaminants (pre-exposure) as shown in Section 2.4.3.2.
- Site topography, the direction of contaminants is controlled by the topography of the site, therefore this information plays an important role in the assessment of pre-exposure of contaminants (outlined in Section 2.4.3.2).

5.5.3 Potential Hazards

The potential hazards associated with each key information have been synthesised from the literature (Table *5.2* to Table *5.16*). These hazards were developed to be used by experts and other stakeholders during the preliminary assessment to identify the likely hazards. Therefore, they should mainly base on the information of the highest standard. Two essential sources are adopted in this research which is technical literature and the knowledge of experts. To ensure a high quality of information, the technical review only looks at the literature that has been cited by specified journal and conference papers in the field of this paper. Furthermore, the knowledge of experts will be developed through their experience of working in the same field. This is important to make educated decisions and deal with incomplete data, for example, by ranking the importance of information or applying certainty to information. These potential hazards are ranked in terms of their likelihood of occurrence. However, the technical literature was discussed in Chapter 2, while knowledge of experts will be developed through a questionnaire in the next section.

5.5.4 The Conceptual Framework Workflow

The DSS workflow is presented in Figure *5:4*, which consists of fourteen steps that are adopted to conduct a preliminary risk assessment for brownfield sites. These steps established to identify and assess the potential sources, pathways and receptors (‘pollutant/ contaminant linkages’), then the final report will be generated. They can then be used to determine the potential hazards related to each essential information. In this way, depending on the user's selection, different hazards are generated, therefore, providing an informed basis for decision–making.

Source: the first nine steps provide a good indication of potential sources and types of hazards likely to be found on site. It starts with determining the site history, surrounding area, building and old structures, underground services, storage materials and old tanks, previous mining activities, presence of radon, invasive species and made ground.

Pathway: step 10, step 11 and step 12 allow the user to determine the pathways within the preliminary risk assessment involves locating possible routes for migration of contaminants within site. On consultation of the technical literature, three major parameters were identified to affect the pathway of contaminants: site geology, site hydrogeology/ hydrology and the topography of the site.

Receptor: step 13 presents the receptors of hazards in brownfield sites. In reviewing the future land use, the assessor seeks to identify the types of people using the site, and in particular, the critical receptors, who are the most people likely to be exposed or susceptible to the presence of soil contamination. While step 14 identifies the impact of the site conditions son the building materials.

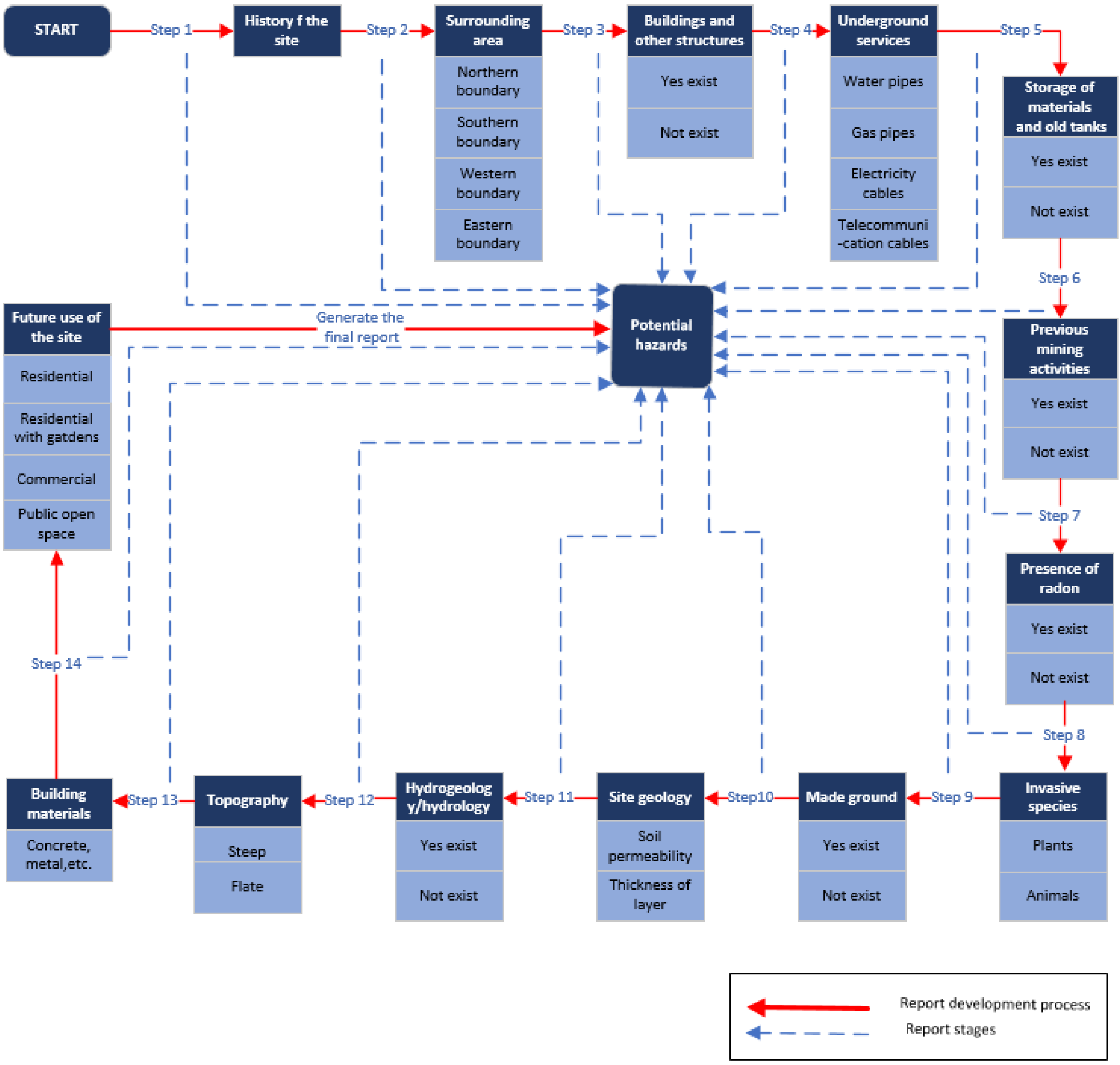

Figure 5:4 The workflow diagram of the conceptual framework

5.6 Chapter Summary

This chapter discussed the development of the proposed conceptual framework to conduct a preliminary risk assessment of brownfield sites by identifying the main concepts and their relationships. Firstly, the pollutant linkage concept was adopted in this research to identify the necessary information for preliminary risk assessment of brownfield sites. Secondly, determine the potential hazards related to each key information. The components of the conceptual framework were determined from a critical review of the literature. Furthermore, this framework is composed of three components, (*i*) pollutant linkage model, (*ii*) site characteristics and (*iii*) potential hazards. The proposed framework is clear and comprehensive to guide research in this field and, ultimately, to shape the development of the DSS.

Framework validation is a significant step to ensure framework validity. The next chapter presents the first part of the validation process via quantitative data collection and analysis.

6. CHAPTER 6: CONCEPTUAL FRAMEWORK VALIDATION

6.1 Introduction

The present chapter discusses the findings from the online survey to validate the developed conceptual framework. To achieve the objectives of this chapter, a questionnaire survey is conducted, which has been thoroughly within Chapter 4. The first phase of the survey rates the required information to identify the pollutant linkage model components (Source-Pathway-Receptor). Otherwise, the second phase prioritises the potential hazards associated with brownfield site using the VAHP method, which helps differentiate the more likely hazards from the less likely ones.

This Chapter is comprised of the following sections:

- Section 6.2 provides the reader with data collection procedures and provides an overview of the survey structure.
- Section 6.3 introduces the different methods adopted in the analysis of the obtained data of the online survey.
- Section 6.4 deals with the reliability of the data collected from the online survey.
- Section 6.5 examines the findings of the primary data, including information related to the profession of the participants and their years of experience.
- Section 6.6 examines Likert scale descriptive analysis and inferential analysis to rate the necessary information to establish the pollutant linkage model.
- Section 6.7 prioritise the potential the hazards associated with brownfield sites.
- Section 6.8 presents participants agreement on the raking of hazards
- Section 6.9 presents a summary of survey analysis findings, including the final version of the conceptual framework.
- Section 6.10 discusses the comments from participants
- Section 6.11 provides a conclusion of this chapter

6.2 Data Collection Procedures

As clarified in Chapter 2, brownfield sites' risk assessment covers a range of disciplines (such as environment, geology, hydrology, geotechnics and chemistry) so brownfield site experts typically come from different backgrounds. Hence, in this study, the experts invited to validate the framework were chosen from a mix of backgrounds but all with professional experience in assessing risks in brownfield sites.

The survey was divided into four sections. The first section presents general demographic questions to determine the participant’s background and years of experience. The second section validates the necessary information to establish pollutant linkage model components (with possible responses from 1= Not important to 5 very important). The third section ranks the hazards associated with brownfield sites, allowing participants to rank a set of items against each other. This type of question has the benefit of requiring respondents to identify how elements or choices compare to each other and determines the most likely ones to them. The fourth section allows the participants to provide comments and suggestions.

6.3 Data Analysis Procedures

The validation process includes many steps, which have been discussed in detail as follow:

1. **Data collection and download:** More than two hundred invitations were sent via email and the LinkedIn website to achieve the right participants. The survey has been left accessible for four months to collect the highest number of responses.
2. **Export data to SPSS:** Once the participant responses data is collected, it will be exported from Qualtrics to SPSS 26 program to make it easy to analysis. The cleaning questionnaire data in SPSS is needed, because incomplete data is expected for reasons like the participants do not know the answer, or do not want to involve in the survey. The analysis considers only the completed answers. Only 76 responses were completed, and most of the incomplete answers come from participants who did not finish the survey and only filled in the general questions or the first questions. However, valid data is important to assess data reliability in this research, which was conducted by adopting the quantitative approach based on SPSS software.
3. **Reliability of data:** In this stage, it is necessary to check the reliability of our survey that was used to collect data to provide effective information that is critical to understand the opinion of the participants (Saunders, 2011). It is important to bring the attention of the reader that reliability of data test is limited only for the second part of the survey

(Likert scale), while in the third part (rank order question), technically those types are inherently negatively correlating because choosing one option for the first variable makes it impossible to select that option for any of the other variables, so the more likely participants are to choose a given option for one variable, the less likely they are to choose it for another variable (Morgan, 2015).

4. **Descriptive analysis**: Once the reliability test is tested, a descriptive statistics method was used to describe, and present data collected from the survey conducted to validate the DSS (Section 4.8.2.2).
5. **Inferential analysis:** After descriptive analysis, an inferential analysis is conducted to ascertain whether the data collected from participants with different views ad experience can be treated as a whole for presenting a general view of the necessary information to establish the pollutant linkage model and prioritizing the potential hazards associated with brownfield sites, the Kruskal-Wallis H test was conducted to check any statistically significant differences in respondents' views if the difference is statistically identifying the Mann–Whitney U test is used to compare differences between two independent groups. Besides, Kendall's W test was used for assessing agreement among participants.
6. **Voting Analytical Hierarchy Process:** VAHP aims to prioritize the potential hazards associated with brownfield sites, identifying and selecting the most appropriate hazards to eventually be more investigated in the next stage of risk assessment. It should be noted that the potential hazards associated with 'site history', 'underground services (telecommunication cables)', 'presence of radon', 'invasive species (animals)' and 'geology' were excluded from the VAHP analysis since it contained only one potential hazard that was identified in this study.

6.4 The Reliability of Questionnaire Data

The reliability test for 49 questions in the survey was first carried out to study the internal consistency. Tavakol and Dennick (2011) argued that, if the alpha value is above 0.70, it indicates a good internal consistency within the data. As shown in Table 6.1, there has been a strong internal consistency for the reliability measures as Cronbach's Alpha more than 0.70.

Table 6.1 The reliability of the survey data tested using Cronbach’s Alpha

Reliability Statistics	
Cronbach's Alpha	N of Items
0.79	49

6.5 Descriptive Analysis of the Primary Data

6.5.1 Professions of the Participants

It is important to identify the profession of the participants to check if they are qualified to answer the questionnaire. Therefore, the participants were asked in an open question format to provide information about their current occupation. The findings of this question are illustrated in

Figure *6:1*. However, the open question format identified seven categories of the profession. This covered Geotechnical Engineer, Geo-Environment Engineer, Hydrogeologist, Geochemist, Geophysicist and Geologist. The largest response came from the Geo-environmental engineer by 16 participants. This reflects that fact that this type is generally involved in the investigation of brownfield sites. In addition, Geotechnical, Hydrogeologist, geophysicist and Geologist represent 13,12,12 and 13 participants respectively. In comparison, Geochemist was the group with the lowest number of participants by 10.

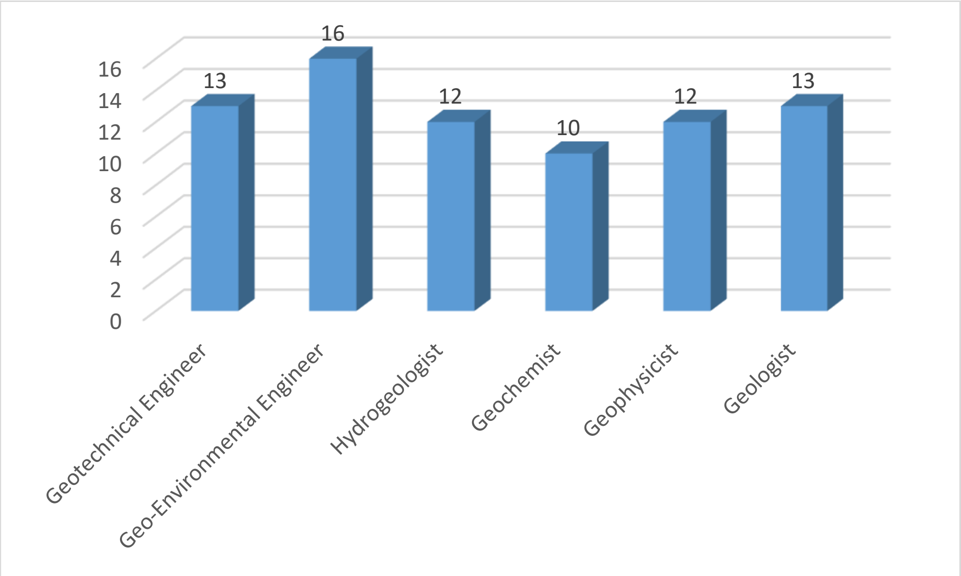

Figure 6:1 The professions of the participants

6.5.2 Professional Experience

The experience of participants in their career is presented in Figure 6:*2*. 68 % of participants had more than six years, 12% have four to six years of experience, and 20% had between one and three years in their current position. Otherwise, the experience of participants in the field of brownfield development is shown in

Figure *6:3*. More than half of participants had more than six years' experience, 25 % had between four and six years, 14 % had between one and three-year of experience.

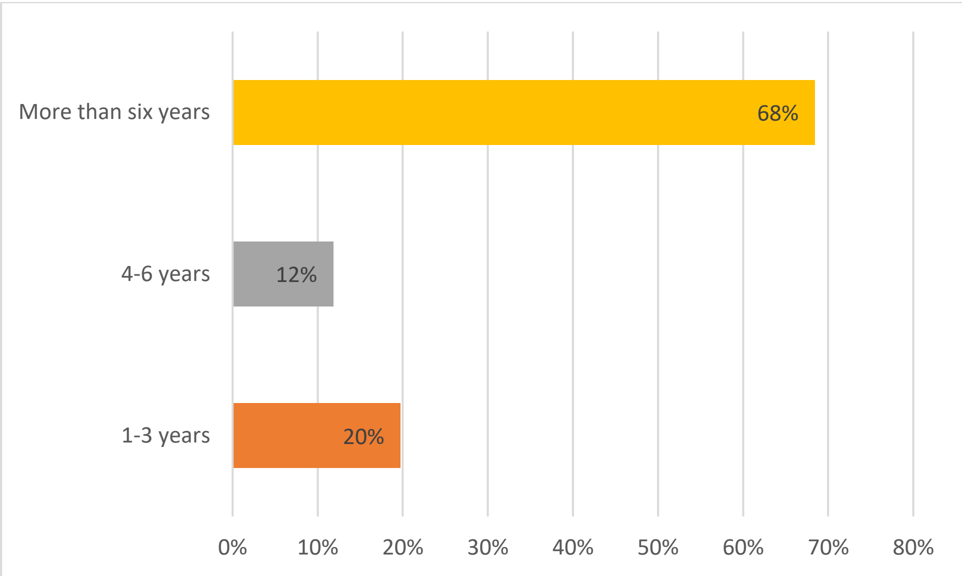

Figure 6:2 Participant experience

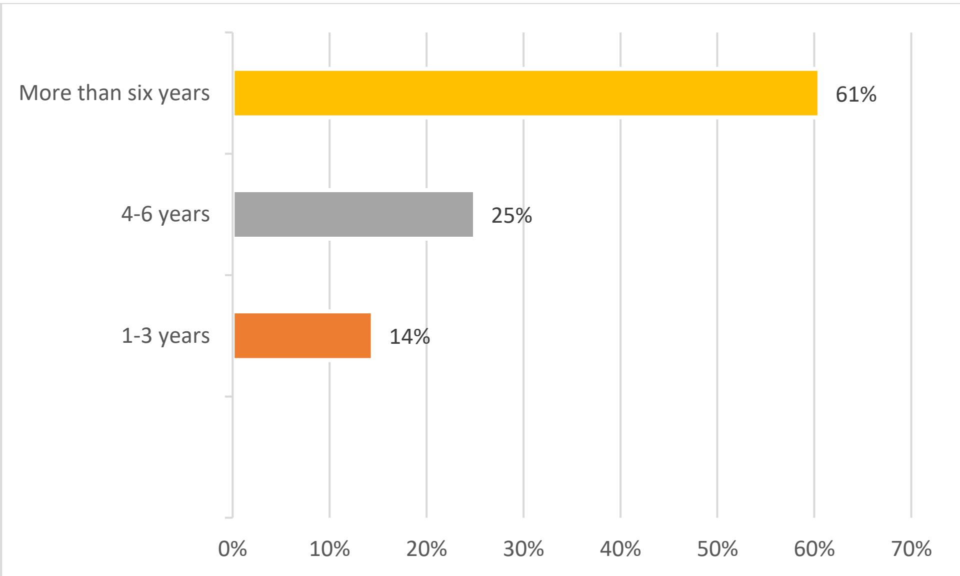

Figure 6:3 Participants experience in the development of brownfield sites

6.6 The Required Information to Establish Pollutant Linkage Model

6.6.1 Obstruction Hazards

6.6.1.1 Descriptive analysis

The respondents were asked to rate the importance of information to identify obstructions in brownfield sites with a five-point rating scale (1=not important, 2=less important, 3=neutral, 4 important, and 5 very important). Table *6.2* shows summary statistical data for the importance of information to identify obstruction in brownfield sites, the results reveal that the highest averages were awarded to buildings and other structures with mean = 4.88; SD=0.325 followed by underground services, storage of materials and old tanks, site history, previous mining activities with mean = 4.87; SD = 0.340, mean = 4.84; SD = 0.367, mean = 4.74; SD = 0.500, mean = 4.72; SD= 0.532, respectively. While, the lowest averages were awarded to made ground with mean =1.51; SD = 0.757, followed by presence of radon with mean =1.14; SD = 0.354, invasive species with mean =1.14; SD = 0.390, followed by surrounding areas by mean =1.05; SD = 0.225.

Table 6.2 Descriptive analysis of obstruction hazards (n=76)

Information	Mean	Median	SD
Site history	4.74	5	0.500
Surrounding areas	1.05	1	0.225
Building and other structures	4.88	5	0.325
Underground services	4.87	5	0.340
Storage of materials and old tanks	4.84	5	0.367
Previous mining activities	4.72	5	0.532
Presence of radon	1.14	1	0.354
Invasive species	1.14	1	0.390
Made ground	1.51	1	0.757

6.6.1.2 Inferential analysis

Before analysing the collected data, the normal distribution of data was tested using the Shapiro-Wilk test. The results indicated that the data collected are not normally distributed, as all the p-values produced by the test were <0.05. Hence, the non-parametric Kruskal-Wallis H test was adopted for intergroup comparison, while Kendall’s coefficient of concordance (concordance test) was used to check the level of agreement among groups.

The same procedures show that the data are not normally distributed with Source-Pathway-Receptor. Therefore, this process is not presented in the next sections to avoid repetition. Kruskal-Wallis H test was carried out using SPSS 26 program to confirm whether there are any statically significant differences in respondents' perception based on their professional roles on the rating of the importance of information (i.e. site history, surrounding areas, buildings and other structures, underground services, storage and tanks, previous mining activities, presence of radon, invasive species and made ground) on identifying the obstructions in brownfield sites. While the p-value <0.05 would reveal a noteworthy difference in the perception of the respondents. The results presented in Table *6.3* show that the respondents do not differ based on their roles, as none of the factors has its Kruskal-Wallis H test coefficient < 0.05. Moreover, Kendall's W test result of 0.910 with the small associated level of significance of 0.000 implied a significant degree of agreement between the respondents regarding the necessary information to identify obstruction hazards in brownfield sites. This signifies a strong consensus among the six professional roles on the importance rating of information to determine the potential obstructions. It is evident that the participants have a good understanding of the appropriate information to identify brownfield sites' obstacles. The outcome of the inferential analysis is presented in Table *6.3*.

Table 6.3 Inferential analysis to identify obstruction hazards in brownfield sites

Information	**Kruskal–Wallis H**		**Kendall's coefficient of concordance**		
	X^2	***P-value***	**W**	***X^2***	***P-value***
Site history	1.376	0.967[a]	0.910	553.556	0.000[b]
Surrounding areas	6.059	0.417[a]			
Building and other structures	3.034	0.804[a]			
Underground services	5.555	0.475[a]			
Storage of materials and old tanks	1.333	0.970[a]			
Previous mining activities	2.944	0.816[a]			
Presence of radon	1.852	0.933[a]			
Invasive species	3.681	0.720[a]			
Made ground	2.324	0.888[a]			

[a]The Kruskal–Wallis H test result is insignificant at the 0.05 significance level (p-value > 0.05); [b]The Kendall's W for rating the information was 0.910 with a significance level of 0.000.

6.6.1.3 Summary

For research rigour, only information with mean scores higher than 3.40 was important (explained in Section 4.8.1.3). This approach was adopted from Pimentel (2010) and does not only determine the necessary information to identify pollutant linkage model, but also reduce the large number of information to reasonable number to allow reliable and effective risk assessment. Therefore, the main information to identify obstruction in brownfield sites are buildings and other structures (mean = 4.88; SD = 0.325), underground services (mean = 4.87; SD = 0.340), storage of materials and old tanks (mean = 4.84; SD = 0.367), site history (mean = 4.74; SD = 0.500) and previous mining activities (mean =4.72; SD=0.532). These outcomes can be explained as follows:

- Buildings and other structures exist in brownfield sites raise concerns about demolition activities. For example, asbestos can be found in any industrial facilities or residential building built or refurbished before 2000.
- Underground services information agrees with previous studies' findings in the context of developing previously used sites. HSE, (2004) highlights the hazards that may cause underground services, where underground electrical cables carry considerable hazardous because they often look like pipes and it is hard to know if they are live just by looking at them. Gas pipes can be exposed to damages when the work is carried out, which may cause leaks that lead to fire or explosion. Otherwise, damage to water pipes is less likely to result in injury, where leaks of water from underground pipes can affect adjacent services and reduce support for other structures (HSE, 2004).
- Storage of materials and tanks presents a potential obstruction to redevelopment, which can have a major significance when discovered during construction if not foreseen and planned for. Additional problems arise during demolition activities, for instance, workers can be injured falling from edges, through openings, fragile surfaces and partially demolished floors.
- Site history provides a good indication of potential obstruction (. i.e. hangars and ancillary workshops, electrical transformer, etc.). The identification of such hazards is reasonably simple, as manufacturing processes, materials and waste of past industries are well documented. However, a full series of forty–eight industrial profiles that give rise to brownfield sites problems have been identified by the UK Environment Agency (2008).

- Previous mining activities, usually have deep basement structures, filled in on a derelict site and no longer evident. These structures, underground pipe runs, tanks, etc. are easily interpreted and located by experts from the industry concerned.

6.6.2 Ground Movement

6.6.2.1 Descriptive analysis

The participants were asked to rate the importance of information to identify ground movement in brownfield sites with a five-point rating scale (1 = not important, 2 = less important, 3 = neutral, 4 = important, and 5 = very important). Table 6.4 shows that the information of made ground (mean = 4.63; SD = 0.608), previous mining (mean=4.24; SD = 0.781), site history (mean=4.08; SD = 0.648) and storage of materials and old tanks (mean = 3.83; SD = 0.915) are ranked very important with highest mean score, followed by invasive species with mean =3.38; SD=0.821. While, building and other structures (mean =1.36; SD =0.667), underground services (mean =1.3; SD = 0.589), surrounding areas (mean =1.03; SD = 0.161) and presence of radon (mean =1.03; SD = 0.229) are ranked not important. This mean this information are not able to help assessors to identify the obstruction. The mean, median and standard deviation for the necessary information to identify obstruction are also shown in Table 6.4.

Table 6.4 Descriptive analysis of ground movement hazards in brownfield sites (n = 76)

Information	Mean	Median	SD
Site history	4.08	4.00	0.648
Surrounding areas	1.03	1.00	0.161
Building and other structures	1.36	1.00	0.667
Underground services	1.30	1.00	0.589
Storage of materials and old tanks	3.83	4.00	0.915
Previous mining activities	4.24	5.00	0.781
Presence of radon	1.03	1.00	0.229
Invasive species	3.38	5.00	0.821
Made ground	4.63	5.00	0.608

6.6.2.2 Inferential analysis

Table 6.5 shows the Kruskal-Wallis H test results undertaken to confirm if there is any statistically significant difference in the perceptions of the six professionals on the rating of the importance of information on identifying the ground movement in brownfield sites. The results indicated that it is statistically different in the perceptions of the six professionals regarding the importance of storage of material and old tank (X^2 =21.478; p-value

=0.001<0.005) and invasive species (X^2 =22.182; p-value =0.000 <0.005) information to determine the ground movement in brownfield sites. Moreover, Kendall's W test result of 0.816 with the small associated level of significance of p-value =0.000 implied an agreement exists among the respondents' rankings in particular groups regarding the necessary information to identify ground movement hazards in brownfield sites.

Table 6.5 Inferential analysis to identify ground movement hazards in brownfield sites

Information	**Kruskal–Wallis H**		**Kendall's coefficient of concordance**		
	X²	***p-value***	**W**	***X²***	***p-value***
Site history	9.244	0.100	0.816	496.259	0.000[b]
Surrounding areas	8.911	0.113			
Building and other structures	6.640	0.249			
Underground services	0.843	0.975			
Storage of materials and old tanks	21.478	0.001[a]			
Previous mining activities	9.991	0.075			
Presence of radon	4.857	0.434			
Invasive species	22.182	0.000[a]			
Made ground	9.409	0.094			

[a] The Kruskal–Wallis H test result is significant at the significance level of 0.05 p-value < 0.05); [b] The Kendall's W for rating the information was 0.816 with a significance level of 0.000.

Starting with the storage of materials and old tanks, Mann-Whitney–U test was conducted to find the cause of the significant differences, the results are presented in Table 6.6. The results show that the reason for the statistically significant differences is due to that mean rank of geochemist engineering ($\overline{X_1} = 8.75; \overline{X_2} = 8.25; \overline{X_3} = 7.75$) were lower than geo–environmental engineering ($\overline{X_1} = 16.75$), geologist ($\overline{X_2} = 14.88$) and geotechnical engineering ($\overline{X_3} = 15.27$), respectively. The test indicated that this difference was statistically significant, (U_1=32.500, P_1=0.002), (U_2=27.500, P_2=0.012) and (U_3=22.500, P_3=.004) successively. In addition, Mann-Whitney U test shows that there was a significant difference between geophysicists ($\overline{X_4} = 9.75$, $\overline{X_5} = 9.58$ and $\overline{X_6} = 8.92$) on the one hand and geo–environmental engineering ($\overline{X_4} = 18.06$), geologist ($\overline{X_5} = 16.15$) and geotechnical engineering ($\overline{X_6} = 16.77$) on the other hand. The test indicated that this difference was statistically significant, (U_4=39.000, P_4=.001), (U_5=37.000, P_5=.017) and (U_6=29.000, P_6=.004) successively. Mann-Whitney U test also shows that was significant difference between hydrologists ($\overline{X_7} = 10.96$ and $\overline{X_8} = 9.67$) and geo–environmental engineering ($\overline{X_7} = 17.16$) and geotechnical engineering ($\overline{X_8} = 16.08$). The test marked that this difference was statistically significant (U_7=53.500, P_7=.017) and (U_8=38.000, P_8=.019) successively.

Table 6.6 Mann-Whitney U for showing a significant difference for storage of materials and old tanks (n = 76)

Job category	N	Mean rank	Mann-Whitney		
			U	Z	P–value
Geochemist		8.75	32.500	–3.080	0.002
Geo–Environmental engineering		16.47			
Geochemist		8.25	27.500	–2.502	0.012
Geologist		14.88			
Geochemist		7.75	22.500	–2.848	0.004
Geotechnical		15.27			
Geophysicist		9.75	39.000	–3.200	0.001
Geo–Environmental engineering		18.06			
Geophysicist		9.58	37.000	–2.387	0.017
Geologist		16.15			
Geophysicist		8.92	29.000	–2.856	0.004
Geotechnical		16.77			
Hydrologist		10.96	53.500	–2.386	0.017
Geo–Environmental engineering		17.16			
Hydrologist		9.67	38.000	–2.339	0.019
Geotechnical		16.08			

Regarding invasive species information, Mann-Whitney U test was applied to find the cause of the significant differences. The results (Table 6.7) show that the reason for the statistically significant differences is due to that mean rank of geophysicists ($\overline{X_1} = 10.42$, $\overline{X_2} = 8.71$ and $\overline{X_3} = 8.75$) were lower than geo–environmental engineering ($\overline{X_1} = 17.56$) geotechnical engineering, ($\overline{X_2} = 16.96$) and geologist ($\overline{X_3} = 16.92$) respectively. The test indicated that this difference was statistically significant, (U_1=47.000, P_1=.018), (U_2=26.500, P_2=.003) and (U_3=27.000, P_3=.004) successively. Furthermore, Mann-Whitney U test shows that there was a significant difference between hydrologist ($\overline{X_4} = 10.33$, $\overline{X_5} = 8.33$ and $\overline{X_6} = 8.50$) and geo–environmental engineering ($\overline{X_4} = 17.63$), geotechnical engineering ($\overline{X_6} = 17.31$) and geologist ($\overline{X_5} = 17.15$). The test indicated that this difference was statistically significant, (U_4=46.000, P_4=.015), (U_5=22.000, P_5=.001) and (U_6=24.000, P_6=.002) successively. Mann-Whitney U test also shows that was a substantial difference between geochemist ($\overline{X_7} = 8.50$ and $\overline{X_8} = 8.60$) on the one hand and geotechnical engineering ($\overline{X_7} =$

14.69) and geologist ($\overline{X_8} = 14.62$) on the other hand. The test marked that this difference was statistically significant (U_7=30.000, P_7=.013) and (U_8=31.000, P_8=.025) successively.

Table 6.7 Mann-Whitney U test for showing a significant difference for invasive species

N°	Jobcategory	Mean rank	Mann-Whitney		
			U	Z	P–value
1	Geophysicist	10.42	47.000	–2.356	0.018
	Geo-Environmental engineering	17.56			
2	Geophysicist	8.71	26.500	–2.990	0.003
	Geotechnical	16.96			
3	Geophysicist	8.75	27.000	–2.873	0.004
	Geologist	16.92			
4	Hydrologist	10.33	46.000	–2.422	0.015
	Geo–Environmental engineering	17.63			
5	Hydrologist	8.33	22.000	–3.305	0.001
	Geotechnical	17.31			
6	Hydrologist	8.50	24.000	–3065	0.002
	Geologist	17.15			
7	Geochemist	8.50	30.000	–2.475	0.013
	Geotechnical	14.69			
8	Geochemist	8.60	31.000	–2.245	0.025
	Geologist	14.62			

6.6.2.3 Summary

Based on the above analysis, the main information to identify ground movement in brownfield sites are made ground (mean = 4.63; SD = 0.608), previous mining (mean = 4.24; SD = 0.781) and site history (mean=4.08; SD=0.648) and storage of materials and old tanks (mean = 3.83; SD = 0.915). Although the invasive species (mean = 3.38; SD = 0.821) was less than 3.40 but it was marginally important as a number of professionals considered invasive species as important information to identify the ground movement in brownfield sites. These findings can be explained as follows:

- Made ground generally contains fill, which may present a significant issue to foundations of buildings due to the compressibility of the ground. This finding is in strong agreement with studies (Watts and Charles, 1997; Charles and Skinner, 2004) reported that collapses of made ground can happen when fill soils are not adequately compacted, they can compress (settle) under the load of a foundation resulting in damage to the structure. Moreover, research conducted by (Shalaby, 2014) shows most poorly compacted fills undergo a reduction in volume when inundated or submerged for the first time, which if it happens after building construction can cause serious damage.

- Previous mining activities may leave a wide amount of slags that cause expansion on wetting (Charles *et al.*, 2002). There have been numerous failures of structures built on such slags, in the United Kingdom and overseas. According to Sharma and Sivapullaiah (2016), the principle hazards from the presence of slags is that they will expand, possibly after decades after deposition, causing damage to structures and roads.
- Site history plays a role to determine waste material that could cause ground movement. For example, a study conducted by Sivapullaiah, Prasad and Allam (2009) demonstrates that soil swelling in the presence of sulfuric acid is possible due to leaching of persistent potassium ions from between the interlayers.
- Invasive species plants alike can cause significant immense landslides and soil loss. For instance, over two years, two case studies from study sites from Switzerland and the UK containing balsam were monitored for soil changes and compared to that of non–invaded areas using erosion pins and digital callipers. The findings from this study provide scientific evidence to support the observations that soil loss is more significant during winter periods in areas that are colonised by Himalayan balsam (Greenwood and Kuhn, 2014).

6.6.3 Chemical Contaminants Hazards

6.6.3.1 Descriptive analysis

The participants were asked to rate the importance of information to identify obstructions in brownfield sites with a five-point rating scale (1=not important, 2=less important, 3=neutral, 4=important, and 5=very important). Table 6.8 shows the mean, median and standard deviation for the necessary information to identify chemical contaminants in brownfield sites, the results show that "site history" was ranked first with the highest mean (mean =4.75; SD = 0.465). The second, as the respondent rated, was made ground (mean =4.63; SD = 0.538), followed by "surrounding areas" (mean = 4.52; SD = 0.608), presence of radon (mean = 4.43; SD = 0.736), previous mining activities (mean = 4.39; SD = 0.750), storage of materials and tanks (mean = 4.34; SD = 0.809) as third, fourth, fifth and sixth accordingly. The invasive species (mean = 3.74; SD = 0.943) ranked seventh, followed by underground services (mean = 3.47; SD = 0.973) and buildings and other structures (mean = 1.55; SD = 0.681) as, eighth and ninth respectively.

Table 6.8 Descriptive analysis of chemical contaminants hazards in brownfield sites

Information	Mean	Median	SD
Site history	4.75	5.00	0.465
Surrounding areas	4.52	5.00	0.608
Building and other structures	1.55	1.00	0.681
Underground services	3.47	4.00	0.973
Storage of materials and old tanks	4.34	5.00	0.809
Previous mining activities	4.39	5.00	0.750
Presence of radon	4.43	5.00	0.736
Invasive species	3.74	4.00	0.943
Made ground	4.63	5.00	0.538

6.6.3.2 Inferential analysis

The Kruskal–Wallis H test has been used to determine whether there are any statistically significant differences between the score among six (6) groups of participants on the importance of information (i.e. site history, surrounding areas, buildings and other structures, underground services, storage and tanks, previous mining activities, presence of radon, invasive species and made ground) on identifying site contamination. The results indicated no statistical difference in the perceptions of the six professionals, as none of the factors has its Kruskal–Wallis H test coefficient less than 0.05. Kendall's W test result of 0.552 with a small associated level of significance of 0.000 implied a significant degree of agreement between the respondents in a group regarding the necessary information to identify chemical contaminants in brownfield sites. Therefore, the results confirmed the similarity in the perception of professionals about the most appropriate information to identify the chemical contaminants on brownfield sites. However, the inferential analysis is presented below in Table 6.9.

Table 6.9 Inferential analysis to identify chemical contaminants hazards in brownfield sites

Information	Kruskal-Wallis H		Kendall's coefficient of concordance		
	***X*²**	***P-value***	**W**	***X*²**	***P-value***
Site history	6.161	0.405[a]	0.552	335.849	0.000[b]
Surrounding areas	3.883	0.693[a]			
Building and other structures	6.804	0.339[a]			
Underground services	2.851	0.827[a]			
Storage of materials and old tanks	6.552	0.364[a]			
Previous mining activities	7.315	0.293[a]			
Presence of radon	8.984	0.174[a]			
Invasive species	6.644	00.355[a]			
Made ground	1.765	.940[a]			

[a] The Kruskal-Wallis H test result is insignificant at the 0.05 significance level (p-value > 0.05); [b] The Kendall's W for rating the information was .552 with a significance level 0.000.

6.6.3.3 Summary

Based on the above analysis, and for research accuracy, only information with mean scores higher than 3.40 were important (Section 4.10.2). Thus, the main information to identify obstruction in brownfield sites are site history (mean = 4.75; SD= 0.465), made ground (mean = 4.63; SD = 0.538), surrounding areas (mean = 4.52; SD = 0.608), presence of radon (mean = 4.43; SD = 0.736), previous mining activities (mean = 4.39; SD = 0.750), storage of material and old tanks (mean = 4.34; SD = 0.809) and invasive species (mean = 3.74; SD = 0.943). These outcomes can be explained as follows:

- Site history is fundamental to identify the potential contaminants present on the site. It can also provide a useful indicator of the likely location of those contaminants. Chemical pollutants are usually determined utilising a full series of forty–eight industrial profiles provided by the (Environment Agency, 2008).
- Made ground may cause pollution, where liquid waste (Leachate) leaking from the ground made is a significant issue related to ground pollution. (Sarsby, R.W. and Felton, 2006). However, waste is considered 'hazardous' under environmental legislation when it contains substances or has properties that might make it harmful to human health or the environment.

- Surrounding areas known by historical industrial activities can be considered a source of contamination because the behaviour of the site containing contamination is the long–term migration of the contaminants itself to potential receptors. Therefore, the assessor is required to determine the adjacent land use type on the northerner, southern, western and eastern boundaries. Such information is extremely useful to determine whether there is a potential for contamination to be present which could impact on current or future uses of a site and potentially pose a risk to occupiers, neighbours or the wider environment.
- Presence of radon is the most common source of radiation exposure, easily exceeding exposure from nuclear power stations or hospital scans and X–rays. Contamination by radon gas has led to concern over a long-term health of occupants of affected buildings. The risk is higher in those who have lived for many years in a radon–contaminated house
- Previous mining activities mainly leaf a wide range of chemical contaminants, including slags from iron and steel–making processes.
- Storage of materials and old tanks is diverse and may vary within industries and from industry to industry and over time. Chemicals and other liquid raw materials stored in tanks and silos, all of which may leak or result in contamination through spills and leakage. Fuel storage and distribution at industry manufacture are the leading causes of soil and groundwater contamination due to leakage from piping, from underground storage tanks (Demirel and Altin, 2017)
- Invasive species can be a source of chemical hazards that may cause serious health issues including poisoning, scars and blindness if the sap gets into the eyes (Crowl *et al.*, 2008).

6.6.4 Biological Contaminants Hazards

6.6.4.1 Descriptive analysis

The respondents were asked to rate the importance of information to identify biological contaminants in brownfield sites with a five-point rating scale (1=not important, 2=less important, 3=neutral, 4=important, and 5=very important). The mean, median and standard deviation for the necessary information to identify biological contaminants in brownfield sites are shown in Table 6.10. The results reveal that the highest mean was granted to invasive species (mean =4.55; SD = 0.501), followed by the site history (mean = 4.49, SD = 0.663), made ground (mean =4.37; SD = 0.538) and surrounding areas (mean =4.00; SD = 0.879). While the lowest mean was granted to building and other structures (mean=1.42, SD

= 0.595), followed by underground services (mean=1.47; SD = 0.577), presence radon (mean=1.51) and storage of materials and old tanks (mean=1.53; SD = 0.663).

Table 6.10 Descriptive analysis of biological contaminants hazards in brownfield sites

Information	Mean	Median	SD
Site history	4.49	5	0.663
Surrounding areas	4.00	4	0.879
Building and other structures	1.42	1	0.595
Underground services	1.47	1	0.577
Storage of materials and old tanks	1.53	1	0.663
Previous mining activities	1.80	2	00.731
Presence of radon	1.51	1	0.600
Invasive species	4.55	5	0.501
Made ground	4.37	4	.538

6.6.4.2 Inferential analysis

Table *6.11* shows the results of the Kruskal-Wallis H test performed to confirm if there is any statistically significant difference in the perceptions of the six professionals on the rating of the importance of information on identifying the biological contaminants in brownfield sites. The results confirmed the similarity in the perception of professionals about the most appropriate information to identify the obstruction on brownfield sites because the significance values of all the information were >0.05. Moreover, the Kendall's W test result of 0.823 with the small associated level of significance of 0.000 implied that there was a significant degree of agreement between the respondents in a particular group regarding the necessary information to identify chemical contaminants in brownfield sites. This signifies a strong agreement among the six professionals of participants on the importance rating of information to determine the potential chemical contaminants.

Table 6.11 Inferential analysis to identify chemical contaminants hazards in brownfield sites

Information	Kruskal-Wallis H		Kendall's coefficient of concordance		
	X^2	*P-value*	W	*X^2*	*P-value*
Site history	4.751	0.576[a]	0.823	500.305	0.000[b]
Surrounding areas	3.407	0.756[a]			

Building and other structures	5.155	0.524[a]
Underground services	11.101	0.088[a]
Storage of materials and old tanks	3.474	0.747[a]
Previous mining activities	1.673	0.947[a]
Presence of radon	12.349	0.055[a]
Invasive species	5.239	0.514[a]
Made ground	3.961	0.682[a]

[a] The Kruskal–Wallis H test result is insignificant at the 0.05 significance level (p-value > 0.05); [b] The Kendall's W for rating the information was .823 with a significance level <0.000.

6.6.4.3 Summary

Based on the above analysis, the main information to identify obstruction in brownfield sites are invasive species (mean=4.55, SD = 0.501), site history (mean=4.49; SD = 0.663), made ground (mean =4.37; SD = 0.538) and surrounding areas (4.00; SD = 0.879). These explained as follows:

- Invasive species usually colonise brownfield sites by invasive animals and plants that may cause problems for human health and buildings' safety. According to (Mazza *et al.*, 2013), invasive alien species are similar to pollutants and maybe even more dangerous than chemicals in the invaded areas. They reproduce and propagate independently, and as a result, even if they cease their activities, their negative effects continue and often increase over time.
- Site history, industries and activities include sewage, hospital waste, landfills, canals, laboratory waste, biodegradable domestic waste and disease/burial pits are the primary source for bacteria, fungi, parasites and viruses. These sources are capable of causing the disease to humans, animals and plants.
- Made ground, sometimes raise concerns about wastes contaminated with biological materials, which could lead to disease if precautions are not taken to reduce the risks. Some of these diseases can be serious or fatal. Exposure to these cause a variety of health effects ranging from skin irritation and allergies to infections (e.g., tuberculosis, AIDS) (Dippenaar *et al.*, 2017).
- Surrounding areas known by industrial activities can be considered a source of biological contamination, which may migrate to potential receptors. Therefore, the assessor is required to determine the adjacent land use type on the northerner, southern, western and eastern boundaries. Such information is extremely useful to

determine whether there is a potential for biological contamination to be present which could impact on current or future uses of a site and potentially pose a risk to occupiers, neighbours or the wider environment.

6.6.5 Biodegradable Effects Hazards

6.6.5.1 Descriptive analysis

The participants were asked to rate the importance of information to identify biodegradable effects in brownfield sites with a five-point rating scale (1=not important, 2=less important, 3=neutral, 4=important, and 5=very important). Table 6.12 shows the mean, median and standard deviation for the necessary information to identify biodegradable effects in brownfield sites. The results reveal that the highest averages were awarded to made ground (mean =4.53; SD = 0.663), followed by site history (mean=4.39; SD = 0.634) and surrounding areas (mean=3.97; SD = 0.588). While, the lowest averages were awarded to underground services (mean=1.80; SD =0.817)and invasive species (mean =1.70; SD =0.833), followed by building and other structures (mean =1.66; SD =0.684), storage of materials and tanks (mean=1.54; SD = 0.682), previous mining activities (mean=1.61; SD = 0.613) and presence of radon (mean=1.61; SD =0.713).

Table 6.12 Descriptive analysis of biodegradable effects in brownfield sites

Information	Mean	Median	SD
Site history	4.39	4.00	0.634
Surrounding areas	3.97	4.00	0.588
Building and other structures	1.66	2.00	0.684
Underground services	1.80	2.00	0.817
Storage of materials and old tanks	1.54	1.00	0.682
Previous mining activities	1.61	2.00	0.613
Presence of radon	1.61	1.00	0.713
Invasive species	1.70	2.00	0.833
Made ground	4.53	5.00	0.663

6.6.5.2 Inferential analysis

Kruskal–Wallis H test was performed to check the differences or similarities in participants' perception of the information to identify biodegradable effects in brownfield sites. The results presented in Table *6.13* confirmed that the individual groups did not differ significantly, as none of the factors has its Kruskal-Wallis H test coefficient less than 0.05. Also, Kendall's W test result of 0.701 with the small associated level of significance of 0.000 implied a significant degree of agreement between the respondents in a group regarding the necessary information to identify biodegradable effects in brownfield sites.

Table 6.13 Inferential analysis to identify biodegradable effects hazards in brownfield sites

Information	Kruskal–Wallis H		Kendall's coefficient of concordance		
	X^2	*P-value*	W	X^2	*P-value*
Site history	5.417	0.367[a]	0.701[b]	426.168	<0.001
Surrounding areas	4.651	0.460[a]			
Building and other structures	3.999	0.550[a]			
Underground services	2.838	0.725[a]			
Storage of materials and old tanks	10.234	0.069[a]			
Previous mining activities	6.264	0.281[a]			
Presence of radon	3.456	.630[a]			
Invasive species	5.007	.415[a]			
Made ground	3.435	.633[a]			

[a] The Kruskal–Wallis H test result is insignificant at the 0.05 significance level (p–value > 0.05); [b] The Kendall's W for rating the information was .701 with a significance level of 0.000.

6.6.5.3 Summary

Based on the above analysis, the main information to identify biodegradation effects in brownfield sites are made ground (mean = 4.57; SD = 0.663), site history (mean=4.42; SD = 0.634) and surrounding areas (mean=3.97; SD = 0.588). These explained as follows:

- Made ground: during the long process of decomposition, a significant decrease in volume and consequent made ground stability is associated with gas generation and leachate formation.
- Site history generally provides a good indication of former waste disposal sites that contain biodegradable materials.
- Surrounding areas, investigators are required to determine the type of surrounding areas on the northern, southern, western and eastern borders. This information is critical to determine if there is a potential for biodegradation in existence which may affect current or future uses of the site and may pose a risk to occupiers, neighbours or the wider environment.

6.6.6 Contaminants Movement

6.6.6.1 Descriptive analysis

The respondents were asked to rate the importance of information to assess contaminants migration in brownfield sites with a five-point rating scale (1=not important, 2=less important, 3=neutral, 4 = important, and 5 = very important). Table *6.14* shows the descriptive analysis, including the mean, median and standard deviation for the necessary information to assess pollutants migration. In addition, it reveals that the site geology (i.e., soil permeability and soil thickness) (mean = 4.64; SD = 0.559), site hydrogeology (presence of groundwater) (mean = 3.67; SD = 0.999), site hydrology (presence site of surface water) (mean = 4.53; SD= 0.598) and topography (mean= 3.74; SD= 0.737) rated very important.

Table 6.14 Descriptive analysis of contaminants movement information

Information	Mean	Median	SD
Site geology (i.e., soil permeability and thickness)	4.64	5	0.559
Site hydrogeology (i.e., presence of groundwater)	3.67	4	0.999
Site hydrology (i.e., presence of surface water and flood zones)	4.53	5	0.598
Site topography (i.e., flat site and steep site)	3.74	4	0.737

6.6.6.2 Inferential analysis

Table 6.15 shows the results of the Kruskal-Wallis H test carried out to confirm if there is any statistically significant difference in the perceptions of the six professionals on the rating of the important information on assessing the contaminant pathway in brownfield sites. It can be seen that all information does not show a significant difference between job categories. This signifies that there is a strong agreement among the six professionals of participants on the importance rating of information to determine the potential obstructions. It is evident that the participants have a good understanding of the parameters that affect contaminants' movement.

Table 6.15 Inferential analysis to identify chemical contaminants hazards in brownfield sites

Information	Kruskal–Wallis H		Kendall's coefficient of concordance		
	X^2	*P-value*	W	X^2	*P-value*
Site geology	10.214	0.069	0.339	77.354	0.000

Site hydrogeology (i.e., presence of groundwater)	1.217	0.943
Site hydrology (i.e., presence of surface water)	2.927	0.711
Site topography	3.415	0.636

[a] The Kruskal–Wallis H test result is insignificant at the 0.05 significance level (p–value > 0.05); [b] The Kendall's W for rating the information was 0.339 with a significance level 0.000.

6.6.6.3 Summary

- Soil permeability parameter is one of the most important factors within the pathway process. This reflects the fact that contaminant movement is more likely in a highly permeable layer than an impermeable layer.
- Soil thickness parameter also plays an essential role when assessing contaminants pathway movement, as the thicker the layer the longer take the contaminants to move through it, which increase the risk of pollutants stagnate while decreasing the risk of contaminants movement to adjacent sites (Briish Standard, 1990).
- Soil hydrology plays a critical role when assessing possible pathway because it influences the movement of potential contaminants on and in the vicinity of a site, and the potential exposure pathways to human health and environmental receptors. The presence of groundwater assists the movement of contaminants, therefore increasing the risk.
- Site topography plays an important role in identifying the direction of the contaminant pathway. In relation to steep sites, pollutants migrate in the direction of the slope, while flat sites can be a challenge because they increase infiltration and vertical movement of pollutants (Environment Agency, 2008; Boulding, 2017).

6.6.7 Receptors

6.6.7.1 Descriptive analysis

The participants were asked to rate the importance of information to identify potential targets brownfield sites with a five-point rating scale (1=not important, 2=less important, 3=neutral, 4 important, and 5 very important). The mean, median and standard deviation related to this question are shown in Table *6.16* below. The results reveal that the highest mean was granted to future user of the site (mean = 4.86; SD = 0.896), followed building materials (mean = 3.45; SD = 0.768).

Table 6.16 Descriptive analysis of receptor information

Information	Mean	Median	SD
Future user	4.86	5	0.896
Building materials	3.47	3	0.768

6.6.7.2 *Inferential analysis*

The results of Kruskal-Wallis H test show that all information does not show a significant difference between job categories. This signifies that there is a strong agreement among the six professionals of participants on the importance of information related to future user and building materials to determine the potential targets. The outcome of inferential analysis is presented in Table *6.17*.

Table 6.17 Inferential analysis to identify chemical contaminants hazards in brownfield sites

Information	Kruskal-Wallis H		Kendall's coefficient of concordance		
	X^2	*P-value*	W	X^2	*P-value*
Future user	4.125	0.665[a]	0.457	57.548	0.000[b]
Building materials	3.564	0.789[a]			

[a] The Kruskal-Wallis H test result is insignificant at the 0.05 significance level (p-value > 0.05); [b] The Kendall's W for rating the information was 0.457 with a significance level 0.000.

6.6.7.3 *Summary*

Based on the above analysis, the receptor is identified by future use information(mean=4.86; SD=0.896).and building materials(mean=3.47; SD=0.768). These can be explained as follows:

- Future end use, the assessor seeks to identify the types of occupant of the site, in particular, the critical receptors, who are the most people likely to be exposed or susceptible to the presence of soil contamination.
- Building materials that are in contact with the ground are often subjected to aggressive environments that cause physical or chemical changes. These changes may result in loss of strength or other changes that will put at risk their structure stability (Garvin, et al., 1999).

6.7 Ranking Potential Hazards

The previous section analysed the necessary information to identify the three components of pollutant linkage model (Source-Pathway-Receptor). The present Section ranks the potential hazards that have identified in Chapter 5. Like the previous section, the data regarding the potential hazards were subjected to dissimilar statistical analysis using the SPSS 26.0. After descriptive analysis, Kendall's W test was conducted to measure the respondents' agreement regarding the potential hazards' rakings. To assess the likelihood of hazards, the mean weights of potential hazards were calculated by VAHP, which was useful for prioritising, classifying, and generally distinguishing potential hazards from more likely than least likely hazards. VAHP method is described in detail and justified in Section 4.8.2.4.

6.7.1 Potential Hazards Associated with Surrounding Areas

6.7.1.1 Descriptive analysis

The participants were asked to rank potential hazards which were developed from the literature. This question aims to rank the hazards associated with surrounding areas brownfield sites from most likely to least likely ones. The results showed that 60.52% (n=46) of participants ranked "Excavation of the brownfield site…", whereas this was ranked second by 25% (n=19) participants, and third by 14.47% (n=11) participants. The migration of contaminants in the period of heavy rainfall or snowmelt was ranked first only by 14.47% (n=11) participants, and second by 57.89% (n=44) participants followed by 27.63% (n=21) participants ranked as third. Most respondents ranked "Pollutants migrate to neighbour residential…" third by 57.89% (n=44) participants, while this was ranked first by 25% (n=19) participants and second by 17.10% (n=13) participants. The outcome of this question is presented in

Figure *6:4*.

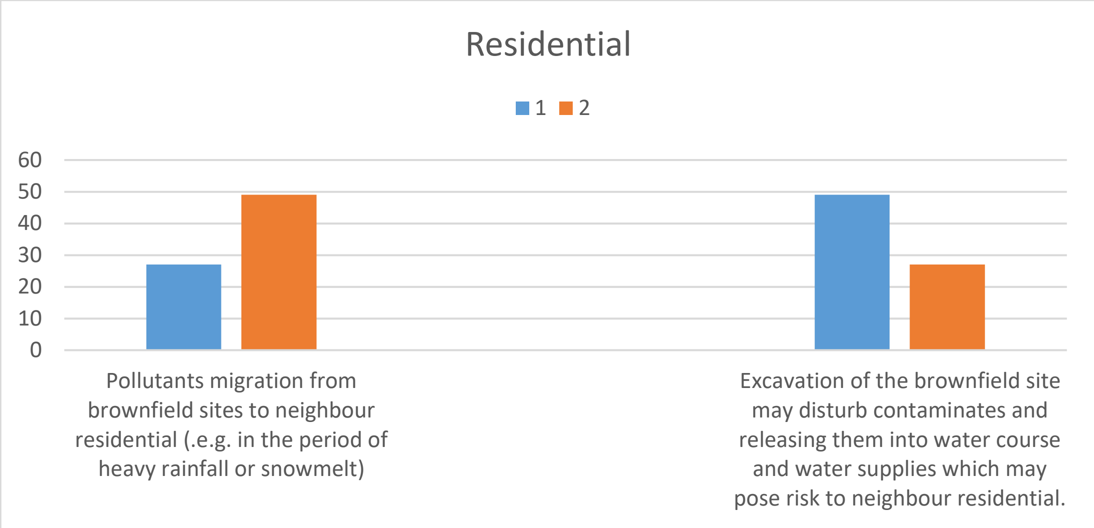

Figure 6:4 Potential hazards associated with the surrounding area (Residential)

Figure 6:5 ranks perceived likelihood of three potential hazards associated with commercial or industrial surrounding areas. Fifty participants ranked “Pollutants migrate to sites…” as first, while ranked second and third by 13 participants equally. “Pollutants migrate from industrial/commercial sites …” ranked second by forty–one participant, followed by 34.21% (n=26) participants ranked third, and 11.84% (n=9) participants ranked first. 48.68% (n=37) participants ranked “Excavation of the industrial site…” as third, while this was ranked first by 22.36 % (n=17) participants and second by 28.94% (n=22)participants.

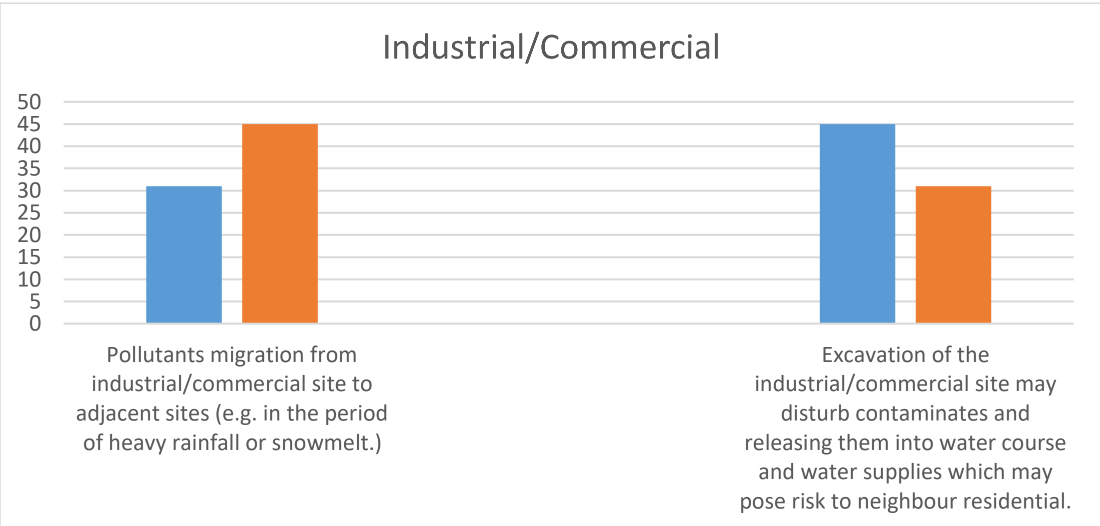

Figure 6:5 Potential hazards associated with surrounding areas (Commercial/Industrial)

6.7.1.2 Ranking potential hazards

The weight of hazards was calculated based on data collected from the survey. This study employed the following sequential steps using equation (3) and (4) (Section 4.8.2.4) of

VAHP model. Ranking of potential hazards has followed the same procedure. Therefore, the results are not presented in the next section to avoid repetition. The steps are presented as follows:

Step 1: calculate the weight of potential hazards: the equation proposed by Hadi–Vencheh and Niazi-Motlagh (2011) for determining hazards weights was applied based on the difference in the number of answers ‘options/places) of each question, the coefficient w_s are different and calculated based on equation (3) detailed in Table *6.18*.

Table 6.18 Coefficient weights according to different options

Formula	Number of places	Coefficient w_s
$w_1 \geq 2w_2 \geq 3w_3 \geq \cdots . \geq Sw_s$ $\sum_{s=1}^{S} w_s = 1$	2	w_1=0.6667 w_2=0.3333
	3	w_1=0.5455 w_2=0.2727 w_3=0.1818
	4	w_1=0.4800 w_2=0.2400 w_3=0.1600 w_4=0.1200
	5	w_1=0.4379 w_2=0.2189 w_3=0.1459 w_4=0.1094 w_5=0.0875
	6	w_1=0.4082 w_2=0.2041 w_3=0.1361 w_4=0.1020 w_5=0.0816 w_6=0.0680
	7	w_1=0.4081 w_2=0.2040 w_3=0.1360 w_4=0.1020 w_5=0.0816 w_6=0.0680 w_7=0.0583
	8	w_1=0.3680 w_2=0.1840 w_3=0.1226 w_4=0.0920 w_5=0.0736 w_6=0.0613 w_7=0.0525 w_8=0.0460
	9	w_1=0.3535 w_2=0.1767 w_3=0.1178 w_4=0.0883 w_5=0.0707

		w_6=0.0589 w_7=0.0505 w_8=0.0441 w_9=0.0392

Step 2–calculate weights and rank hazards by using VAHP equation 5: $\theta_r = \sum_{s=1}^{S} x_{rs} w_s \quad r = 1,2, \ldots., R.$

For example, for the potential hazards associated with surrounding areas: "Excavation of the brownfield site…", "Migration of contaminants to neighbour residential in the period of heavy rainfall or snowmelt", "Migration to neighbour residential…". Therefore, by using the equation (4), the value of w_s will be: w_1 = 0.545455, w_2= 0.272727, and w_3 = 0.181818. Base on the number of votes obtained from the online survey, the total weight of potential hazards as below:

Residential

- "Excavation of brownfield site may disturb contaminates and releasing them into the water course and water supplies, which may pose a risk to neighbour residential":
  49 × 0.6667 + 27 × 0.3333 = 41.667
- "Pollutants migration from brownfield sites to neighbour residential (e.g. in the period of heavy rainfall or snowmelt)":
  27 × 0.6667 + 49 × 0.3337 = 34.332

Industrial/Commercial

- "Excavation of brownfield site may disturb contaminates and releasing them into water course and water supplies which may pose risk to neighbour residential":
  45 × 0.6667 + 31× 0.3333 = 40.333
- "Pollutants migration from industrial/commercial site to adjacent sites (e.g. in the period of heavy rainfall or snowmelt.).":
  31 × 0.6667 + 45 × 0.3333 = 35.666

Subsequent to the calculation of weights, the obtained weights for the potential hazards were normalised so that they add up to one. Similarly, the obtained weights for the attributes in hazard were normalised.

Figure 6:6 The weights of the potential hazards associated with surrounding areas

Surrounding areas	Potential hazards	Weight	Normal	Rank

Residential	Excavation of the brownfield site may disturb contaminates and release them into water course and water supplies which may pose risk to neighbour residential.	41.667	0.548	1
	Pollutants migration from brownfield sites to neighbour residential (.e.g. in the period of heavy rainfall or snowmelt)	34.332	0.451	2
Industrial/Commercial	Excavation of the industrial/commercial site may disturb contaminates and releasing them into water course and water supplies which may pose risk to neighbour residential.	40.333	0.530	1
	Pollutants migration from industrial/commercial site to adjacent sites (e.g. in the period of heavy rainfall or snowmelt.)	35.666	0.469	2

This outcome indicates that excavation in brownfield sites is the most likely hazards associated surrounding information. The finding agrees with the results of previous studies (Leach and Goodger, 1991; Wood, 2015; Liu *et al.*, 2018) carried–out in the context of remedial treatment of contaminated sites, where excavation contaminants would be a positive way of preventing contact of pollutants (i.e. chemical and biological) with surface targets and the aquifer, but the disturbance of contaminants can create a high risk that migrating contaminants into groundwater or adjacent sites. The second, as the respondents ranked was pollutant migration to adjacent sites, this finding agrees with (Leach and Goodger, 1991), which indicates an important phenomenon in the site containing contamination is the long term transport of pollutants to adjacent sites. For instance, contaminant could migrate in the direction of steep contaminated site. In addition, many studies (Mouri *et al.*, 2014; Hadigheh, Gravina and Smith, 2017) highlight that heavy rainfall or snowmelt may cause the chemicals to leach to neighbours.

6.7.2 Potential Hazards Associated with Buildings and other Structures

6.7.2.1 Descriptive analysis

The participants were asked to rank potential hazards which were developed from the literature. The aim of this question is to rank hazards associated with building and other structures brownfield sites from the most likely to least likely in terms of their occurrence. The results showed that 59.21 % (n=45)of participants ranked "Hazards related to demolition…", whereas this was ranked second by 22.36 % (n=17) participants, and third by 18.42% (n=14) participants. "Hazards from sharps…" was ranked first only by 23.68 %

(n=18) participants, and second by 46.05% (n=35) participants followed by 30.2 6% (n=23) participants ranked as third. Most respondents ranked "Old foundation failure…" third by 51.31 % (n= 39) participants, while this was ranked first by 17.10 % (n=13) participants and second by 31.57 % (n=24) participants. The outcome of this question is presented in Figure *6:7*.

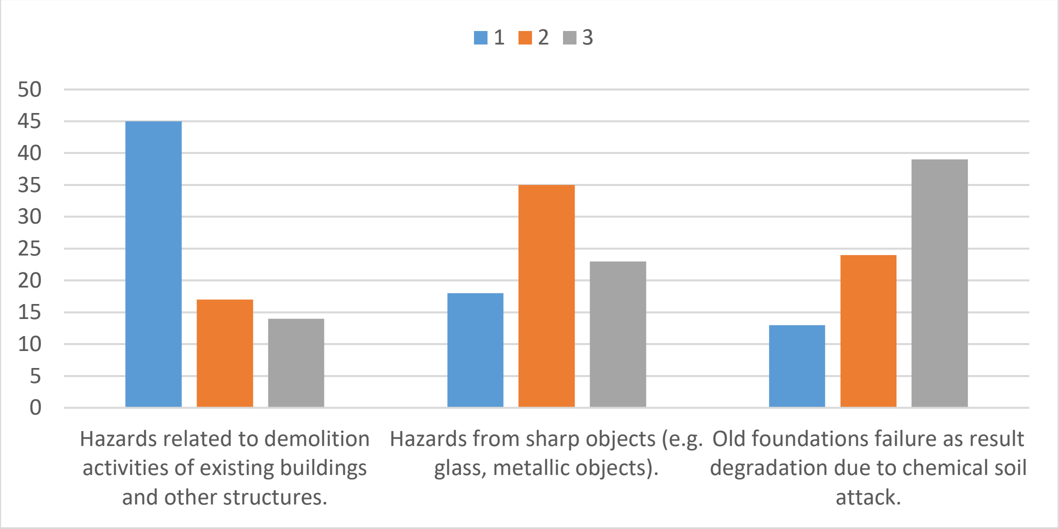

Figure 6:7 Potential hazards associated with buildings and other structures

6.7.2.2 Ranking potential hazards

The participants were asked to rank potential hazards related to surrounding areas information. Table *6.19* shows that "Hazards related to demolition…" was ranked first with the highest weight by 31.727 The second, as the respondents ranked was "Hazards from sharp…" with weight of 23.545, followed by "Old foundations…" with weight = 20.727 as the third most likelihood hazards.

Table 6.19 The weights of the potential hazards associated with buildings and other structures

Potential hazards	Weight	Normal	Rank
Hazards related to demolition activities of existing buildings and other structures.	31.727	0.417	1
Hazards from sharp objects (e.g. glass, metallic objects).	23.545	0.309	2
Old foundations failure as result degradation due to chemical soil attack.	20.727	0.272	3

This outcome is in agreement with studies conducted by (Leach and Goodger, 1991; Barry, 1991; Sarsby, 2000; Charles, 2005), which mentioned that structures and buildings exist on previously used land may present an additional source of hazards during demolition activities. For instance, it can be commonplace on brownfield sites to discover asbestos contamination within the soil when demolition has been completed. Furthermore, buildings originally sited on brownfield land are likely to have contained high levels of contaminants, where the US Environmental Protection Agency (EPA) showed that there is potential widespread use of Asbestos, PCB–containing building materials, Asbestos, Microbiological, Synthetic mineral fibres in schools and other buildings constructed or renovated between about 1950 and 1979.

6.7.3 Potential Hazards Associated with Underground Services

6.7.3.1 Descriptive analysis

Participants were asked to rank potential hazards which were identified from the literature. The purpose was to rank the hazards associated with water pipes brownfield sites from most likely to least likely ones (Figure 6:*8*). The results showed that 40.78 % (n=31) participants ranked "Leaks of water...", whereas this was ranked second by 21.05 % (n=16) participants, and third by 21.05 % (n=16) participants. "Damage to water…" was ranked first only by 17.10 % (n=13) participants, and second by 38.15% (n=29) participants followed by 25% (n=19) participants ranked as third. Most respondents ranked "Damage to sewer…" fourth by 32.89 % (n=25) participants, while this was ranked first by 21.05 % (n=16) participants and second by 17.10 % (n=13) participants. In addition, "Contaminants in the ground…' ranked fourth by 30.26 % (n=23) participants, followed by 25 % (n=19) participants ranked third, and second by 23.68 % (n=18) participants.

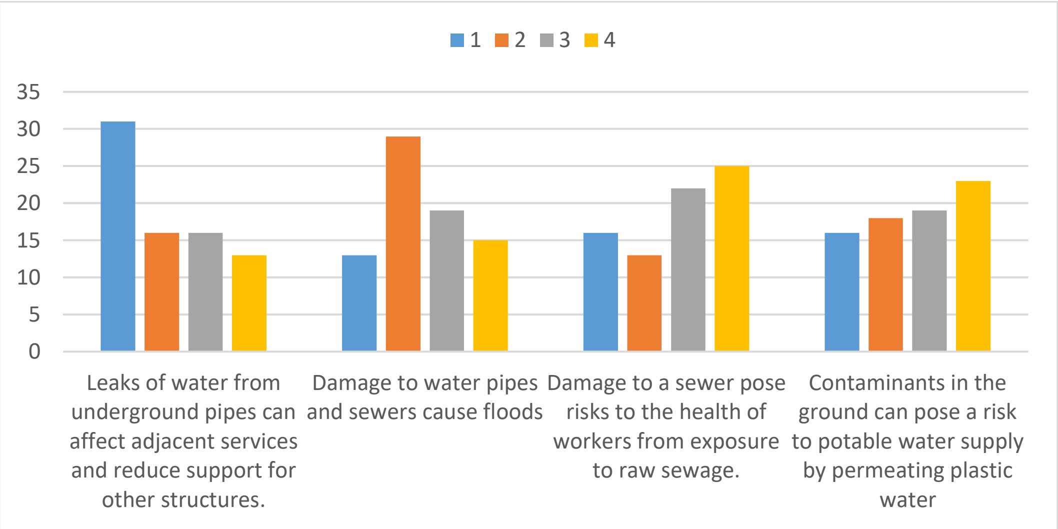

Figure 6:8 Potential hazards associated with underground services (Water pipes)

Figure 6:9 ranks perceived likelihood of four potential hazards associated with underground services (gas pipes). Forty-three participants ranked fire and explosion due to flammable gases as first, while ranked second and third by 14 participants and 9 participants respectively. Leakage due to damage of connections ranked second by 39 participants, followed by 16 participants ranked third, and 14 participants ranked first. Most participants ranked poisoning due to toxic gases third by 36 participants, while this was ranked first by 10 participants and second by 11 participants. Moreover, release of contents due to elevated pressure ranked fifth by 25 participants, followed by 27 participants ranked fourth, and third by 8 participants. Asphyxiation due to inert gases was ranked fifth by 31, and fourth by 23 participants, and third by only 7 participants.

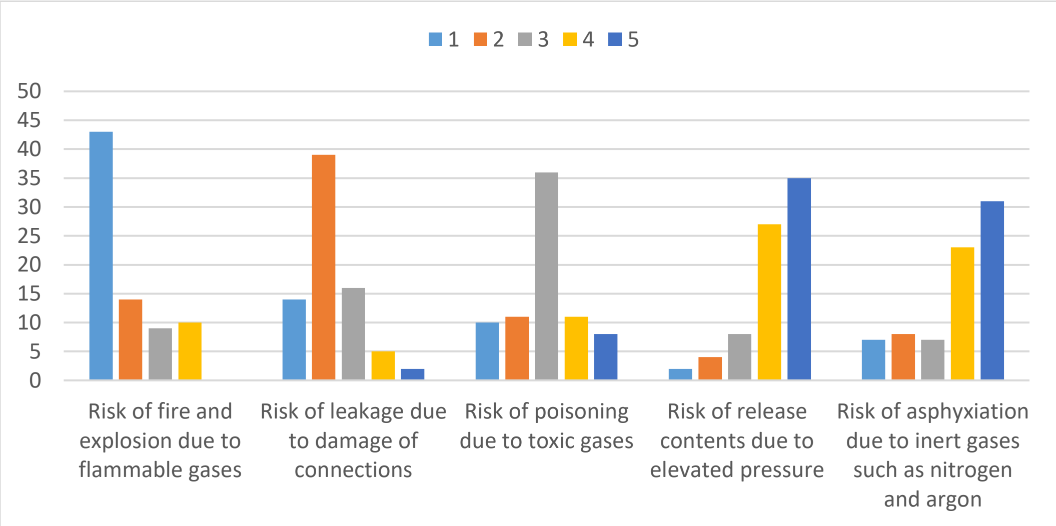

Figure 6:9 Potential hazards associated with underground services (Gas pipes)

Figure 6:*10* ranks perceived likelihood of four potential hazards related to underground services (Electricity cables). Thirty–nine participants ranked “Explosive, fire or flames that...” as the likeliest, with 14 ranked this second, and 10 ranking it third. . “Cables which have been damaged..” was ranked second by 29 participants, first and third by 15 participants and 11 participants respectively. Most of participants ranked “Hazard of electrical cables…” as third by 33, and otherwise by 18 or fewer. “Damage of electricity cables…” was ranked fourth by 32 participants, while this was ranked only by 4 participants as first, otherwise by 18 or fewer.

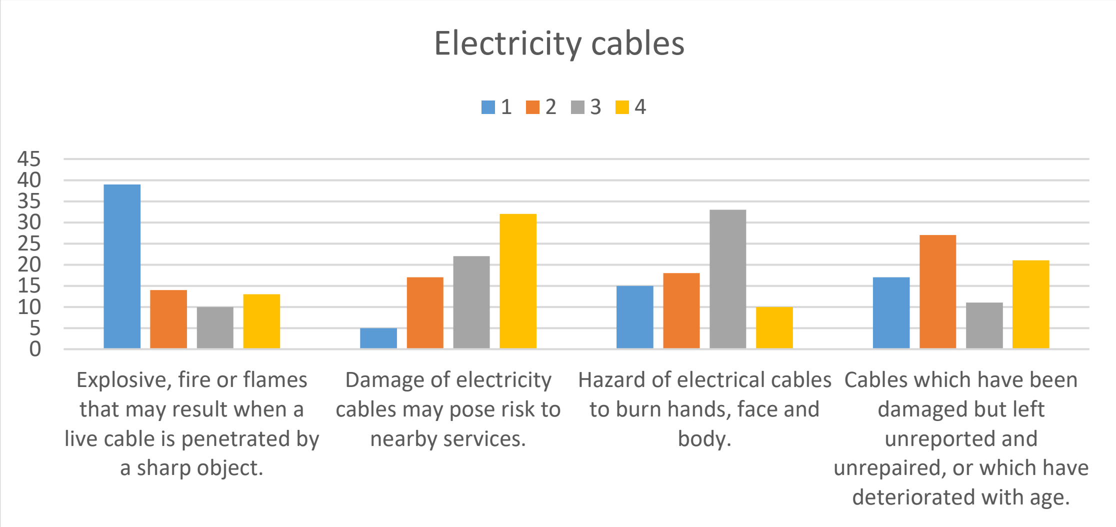

Figure 6:10 Potential hazards associated with underground services (Electricity cables)

6.7.3.2 Ranking potential hazards

As the target of adopting VAHP is to identify the most and the least likelihood of occurrence of hazards associated with brownfield sites, the participants were asked to rank potential hazards related to underground services. Firstly, the ranking order of potential hazards related to water pipes is presented in

Table 6.20, where leaks of water ranked first with the highest weight of 22.84, followed by the damages to water pipes and sewer that may occur during the redevelopment of brownfield sites which may cause floods. While migration of contaminants through permeating water pipes ranked third (weight of 17.80), followed by the damage to sewerage which may pose a risk to site works by weight of 17.32. Secondly,

Table 6.20 shows the ranking order of potential hazards related to gas pipes, where the damage to gas pipes ranked first (weight of 24.30). This is perhaps an expected result as any damage or accidents to gas pipes during the redevelopment of brownfield sites may lead to explosion and fires. Gas pipes also raise concerns of leakage due to damage or lack of maintenance, which may pose a risk for site workers or future occupants. However, this hazard ranked second (weight of 17.72). Otherwise, some gases such as chlorine, phosgene, sulphur dioxide, hydrogen sulphide, nitrogen dioxide, and ammonia which may severely toxic to human health. This potential hazard was ranked third (weight of 13.94). While the risk related to release contents due to elevated pressure ranked fourth (weight of 11.06). The fifth rank was awarded to asphyxiation hazards due to inert gases such as nitrogen and argon by weight of 8.93.Thirdly, incidents (e.g. penetrated by a sharp object) during the redevelopment of brownfield sites may lead to an explosive, fire or flames associated with electricity cables ranked first (weight of 25.24). This understandable as Health and Safety Executive (2010) reported that each year about 1000 accidents at work involving electric shock or burns. Followed by cables that have been damaged but left unreported and unrepaired, or have deteriorated with age. This hazard ranked second (weight of 18.92). While the risk to near services as result of damages of electricity cables ranked fourth (weight of 13.84).

Table 6.20 The weights of the potential hazards associated with underground services

Underground services	Potential hazards	Weight	Normal	Rank
Water pipes	Leaks of water from underground pipes can affect adjacent services and reduce support for other structures	22.84	0.300	1
	Damage to water pipes and sewers may cause floods	18.04	0.237	2
	Contaminants in the ground can pose a risk to potable water supply by permeating plastic water	17.80	0.234	3
	Damage to a sewer pose risks to the health of workers from exposure to raw sewage.	17.32	0.227	4
Gas pipes	Risk of fire and explosion due to flammable gases.	24.30	0.319	1
	Risk of leakage due to damage of connections.	17.72	0.233	2
	Risk of poisoning due to toxic gases	13.94	0.183	3
	Risk of release contents due to elevated pressure	11.06	0.145	4
	Risk of asphyxiation due to inert gases such as nitrogen and argon	8.93	0.117	5
Electricity cables	Explosive, fire or flames that may result when a live cable is penetrated by a sharp object.	25.24	0.332	1
	Cables which have been damaged but left unreported and unrepaired, or which have deteriorated with age.	18.92	0.248	2
	Hazard of electrical cables to burn hands, face and body.	18.01	0.236	3
	Damage of electricity cables may pose risk to nearly services	13.84	0.182	4

6.7.4 Potential Hazards Associated with Storage and Old Tanks

6.7.4.1 Descriptive analysis

The participants were asked to rank potential hazards which was developed from the literature. The aim of this question is to rank the likely and unlikely hazards associated with storage of materials and old tanks. The results showed that 67.10% (n=51) of participants ranked "Chemicals and other liquid...", whereas this was ranked second by 32.89% (n=25) participants. "Ground instability related to removing tanks…" was ranked first by 32.89% (n=25) participants, and second by 67.10% (n=51) participants. The outcome of this question is presented in Figure 6:*11*.

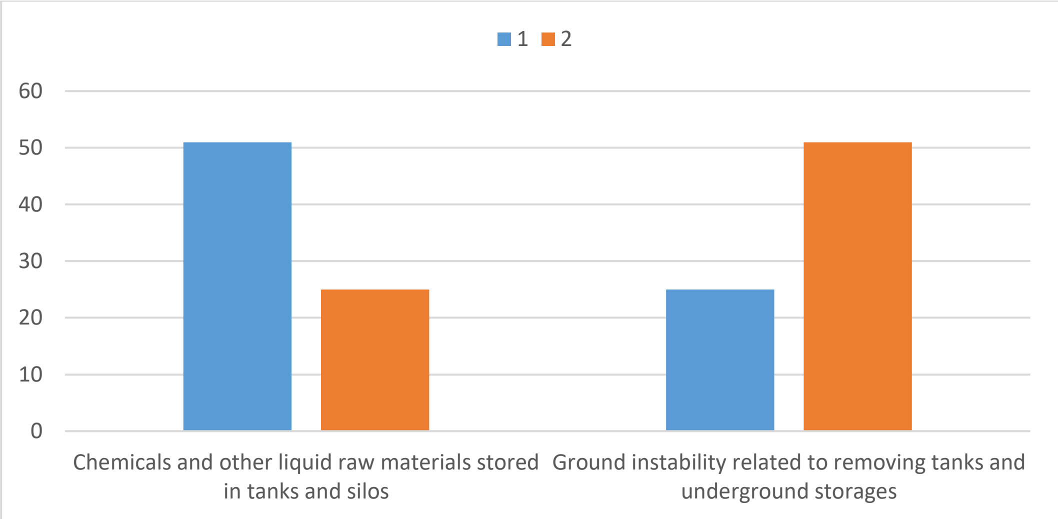

Figure 6:11 Potential hazards associated with storage of materials and old tanks

6.7.4.2 Ranking potential hazards

The participants were asked to rank potential hazards related to storage of materials and old tanks information. Table 6.21 shows that "Hazards related to demolition…" was ranked first with the highest weight by The second, as the respondents ranked was "Hazards from sharp…" with weight of , followed by "Old foundations…" with weight = as the third most likelihood hazards.

Table 6.21 The weights of the potential hazards associated with storage of materials and old tanks

Potential hazards	Weight	Normal	Rank
Chemicals and other liquid raw materials stored in tanks and silos	42.334	0.557	1
Ground instability related to removing tanks and underground storages	33.650	0.443	2

It was not surprising that the chemicals and other liquid raw materials stored in tanks and silos had the highest level of importance, which was demonstrated in many research as one of the main causes of soil and groundwater contamination due to leakage from piping, from underground storage tanks. Section 2.3 outlined also the responsibility of the storage of materials in soil pollution, that delivery and storage facilities are responsible for contaminants to be absorbed on to soil, where contaminants could be dissolved in water and readily migrate through soil system and reaching groundwater. The ground instability was ranked second, this hazard was highlighted in studies (Skinner *et al.*, 2005; Watts and Charles, 2015) , where the ground stability issues are most likely to occur on removal of storages and tanks.

6.7.5 Potential Hazards Associated with Previous Mining Activities

6.7.5.1 Descriptive analysis

The participants were asked to rank potential hazards which was developed from the literature. The aim of this question is to rank the hazards associated with previous mining activities from most likely to least likely ones. The results showed that 61.84% (n=47) of participants ranked "Subsidence and collapsing of voids...", whereas this was ranked second and third by 27.63% (n=21) participants and 10.52% (n=8) participants respectively. "Emission of noxious or asphyxiating…" was ranked first by 22.36% (n=17) participants, second by 55.26% (n=42) participants and third by 22.36% (n=17) participants. Otherwise, most of participants ranked "Spontaneous combustion of coal…" third by 38 participants, followed by 27.63% (n=21) participants as fourth and second by only 9.21% (n=7) participants. Finally, "Pollution incidents…" ranked fourth by 71.05% (n=54) participants, third by17.10% (n=13) participants and second by 9.21% (n=7) participants. The finding of this question is presented in Figure 6:*12*.

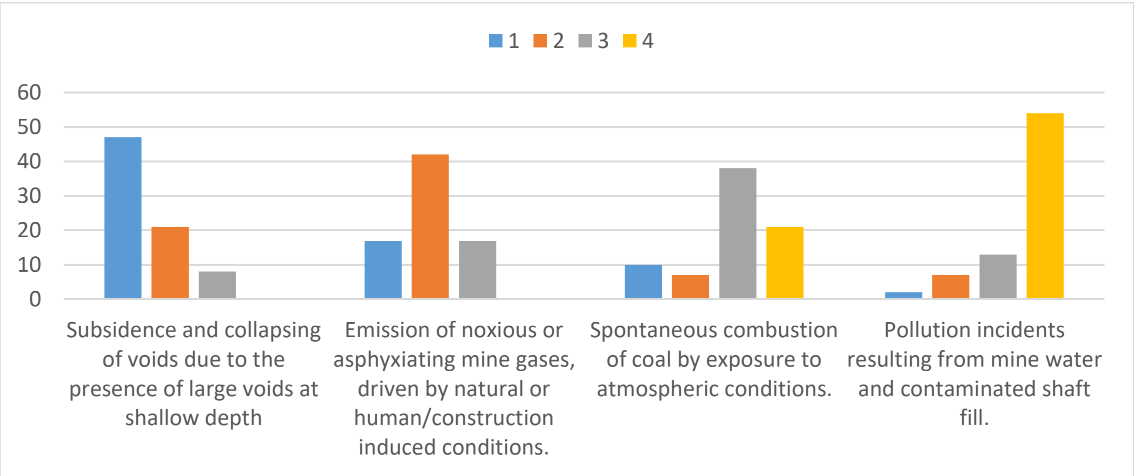

Figure 6:12. Potential hazards associated with previous mining activities

6.7.5.2 Ranking potential hazards

The VAHP analysis shows that "Subsidence and collapsing of voids…" was ranked first with the highest weight of 28.88. Perhaps expected, the hazards related to subsidence of voids in previous mining sites ranked first, this finding could be due to the wide range of f mining subsidence incidents that occurred in sites with mining history. The second, as the respondents ranked was "Emission of noxious or asphyxiating …" with weight of 20.96, this finding is consistent with existing research by Greenwood and Kuhn, 2014, who warned gas seeping from abandoned mine. "Spontaneous combustion of coal" ranked third most likelihood hazards (weight of 0.198.) In addition, spontaneous combustion of coal is a well–known phenomenon around the globe. Serious incidents of spontaneous combustion have been reported as a result of self–heating of reactive coal–shales. Finally, 'Pollution incidents…" had the lowest weight amongst all hazards, as ranked fourth (weight of 0.147). The results are illustrated in Table 6.22.

Table 6.22 The weights of the potential hazards associated with previous mining activities (n=76)

Potential hazards	Weight	Normal	Rank
Subsidence and collapsing of voids due to the presence of large voids at shallow depth	28.88	0.38	1
Emission of noxious or asphyxiating mine gases, driven by natural or human/construction induced conditions	20.96	0.275	2
Spontaneous combustion of coal by exposure to atmospheric conditions.	15.08	0.198	3
Pollution incidents resulting from mine water and contaminated shaft fill	11.2	0.147	4

6.7.6 Potential Hazards Associated with Invasive Species (Plants)

6.7.6.1 Descriptive analysis

The participants were asked to rank potential hazards which was developed from the literature. The aim of this question is to rank the hazards associated with invasive plants from most likely to least likely ones. The results showed that 73.68 % (n= 56) of participants ranked "Health issues due to contact…", whereas this was ranked second by 19.73 % (n=15) participants. "Aggressive plant that can cause damage…" was ranked first by 14.47 % (n=11) participants, and second by 51.31 % (n=39) participants. The landslide caused by species plants was ranked first by 11.84 % (n=9) participants and third by 59.21 % (n=45) participants. The outcome of this question is presented in Figure 6:*13*.

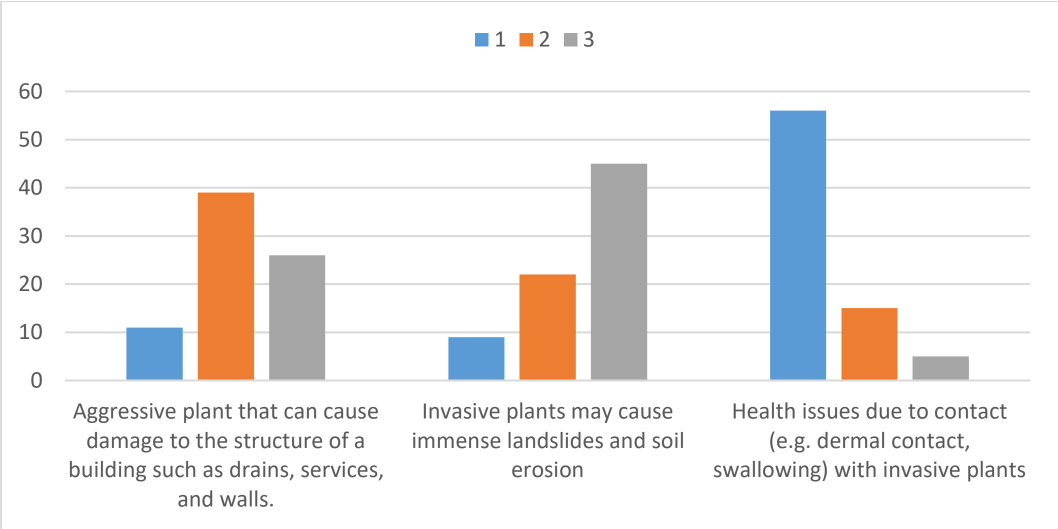

Figure 6:13 Potential hazards associated with invasive species (plants)

6.7.6.2 Ranking potential hazards

The outcome of VAHP analysis shows that "Health issues due to contact …" was ranked first (weight of 35.455). Hence, it is understandable because some plant leaves contain toxic which may affect the human health, for example physical contact with the leaves may cause skin irritation. The second, as the participants ranked was "Aggressive plant that can cause damage…" with a weight of 21.363, this findings was highlighted by research conducted by Payne *et al.* (2012), who discussed the danger of Japanese knotweed to buildings. In addition, Warren (2019) demonstrate that the plant is difficult to remove once established and can regenerate rapidly from small pieces. The presence of Japanese Knotweed must be declared by the seller during conveyancing and some mortgage companies require eradication backed by warranty before they will lend money on a property. Finally, the ground movement due to species plants was ranked third (weight of 19.10), where the literature shows that areas recently supporting the invasive plant, Himalayan Balsam (HB), recorded significantly higher erosion rates than nearby uninvaded areas. The findings of this analysis are presented in Table 6.23.

Table 6.23 The weight of potential hazards associated with invasive species (plants)

Potential hazards	Weight	Normal	Rank
Health issues due to contact (e.g. dermal contact, swallowing) with invasive plants	35.455	0.467	1
Aggressive plant that can cause damage to the structure of a building such as drains, services, and walls.	21.363	0.281	2
Invasive plants may cause immense landslides and soil erosion	19.10	0.251	3

6.7.7 Potential Hazards Associated with Made Ground

6.7.7.1 Descriptive analysis

The participants were asked to rank potential hazards which was developed from the literature. The aim of this question is to rank the hazards associated with made grounds from most likely to least likely in terms of their occurrence. The results showed that 41 of participants ranked first “The migration of contaminants...”, whereas this was ranked second and third by 27.63 % (n=21) participants and 7.89% (n=6) participants respectively. “The generation of methane…” was ranked first by 31.57% (n=24) participants, second by 42.10% (n=32) participants and third by 3.94% (n=3) participants. Otherwise, most of participants ranked “Hazards for buildings…” third by 57.89% (n=44) participants, followed by 14.47% (n=11) participants as fourth and second by 14.47% (n=11) participants too. “Damage to buildings…” ranked fourth by 52.63% (n=40) participants, third by 21.05% (n=16) participants and fifth by 17.73% (n=15) participants. Eventually, “failure of construction…” ranked fifth by 64.47% (n=49) participants and otherwise by 17.73% (n=15) or fewer. The finding of this question is presented in Figure 6:14.

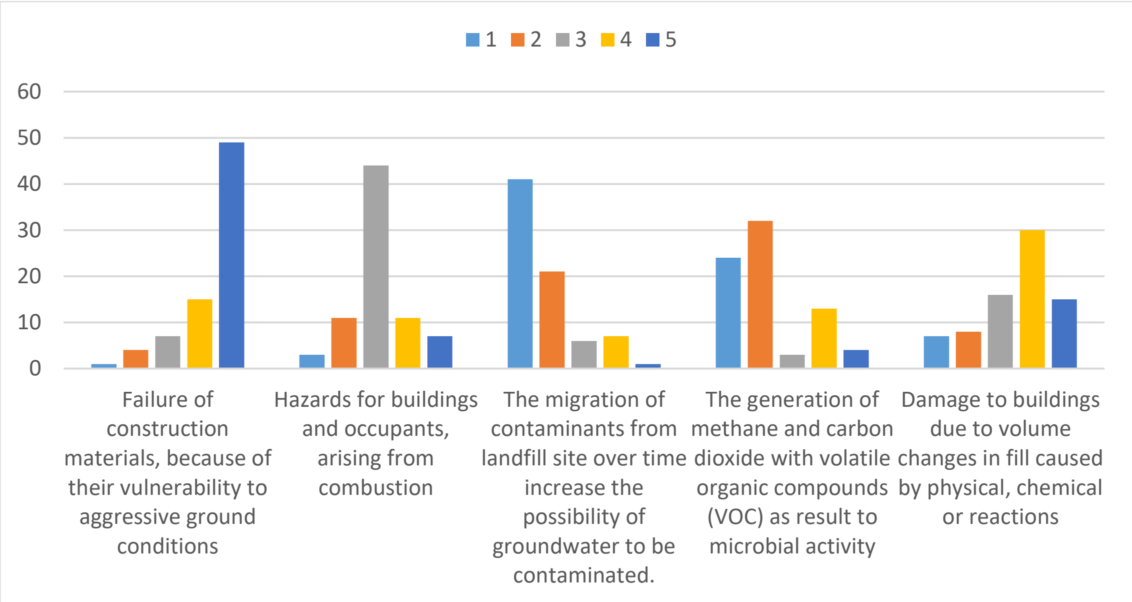

Figure 6:14: Potential hazards associated with made ground

6.7.7.2 Ranking potential hazards

Table 6.24 results indicate that the contaminants from landfill are the most likelihood hazards (weight of 24.279) associated with made grounds. Leach and Goodger (1991) indicate that hazardous leaching from made ground are generally more troublesome. This prompted many scientists to deliver a considerable amount of research to study the consequence of contaminants leaching on groundwater and the aquifers. It is not surprising that the generation of methane from landfill ranked high with a weight of 19.724, this result provides a useful reminder to assessors that hazardous gas may be present in brownfield sites containing made ground where Compton *et al.* (1999) indicated that 250–400 m^3 of landfill gas can be generated from 1 ton of biodegradable waste. Otherwise, made ground combustion ranked third by respondents (weight =11.957). This hazard may result from the oxidation of organic materials and carbonaceous minerals (e.g. coal residues, solvent oils, amongst others.), as well as non–carboniferous materials (e.g. sulphur, zinc blende iron, pyrite and spent oxide in gas work residues). Thus, whenever combustion materials found are precaution must be contemplated.

Made ground may also raise concerns related to settlement which gives rise to the most serious problems for building development on made ground. Even where the suitable remedial measures are taken. In addition, gassing and combustibility hazards may affect the stability of the site. This hazard was ranked fourth by a weight =11.745. Failure of construction materials, because of their vulnerability to aggressive ground conditions ranked fifth (weight of 8.263). This is understandable because aggressive ground conditions on made ground may be less intense than on an industrial contaminated site, due lower concentrations of contaminants.

Table 6.24 The weight of potential hazards associated with made ground

Potential hazards	Weight	Normal	Rank
The migration of contaminants from landfill site over time increase the possibility of groundwater to be contaminated.	24.279	0.319	1
The generation of methane and carbon dioxide with volatile organic compounds (VOC) as result to microbial activity	19.724	0.259	2
Hazards for buildings and occupants, arising from combustion	11.957	0.157	3
Damage to buildings due to volume changes in fill caused by physical, chemical or reactions	11.745	0.154	4
Failure of construction materials, because of their vulnerability to aggressive ground conditions	8.263	0.108	5

6.7.8 Potential Hazards Associated with Site Topography

6.7.8.1 Descriptive analysis

The participants were asked to rank potential hazards which were developed from the literature. This question aims to rank the hazards associated with brownfield site’ topography (flat site) from most likely to least likely ones. The results showed that 68.42% (n=52) of participants ranked first "Horizontal site increase infiltration…", whereas this was ranked second by 23.68% (n=18) participants. "Horizontal sites reduce contaminants…" was ranked second by 68.42% (n=52) participants and first by 23.68% (n=18) participants. The findings of this question are presented in the Figure *6:15*.

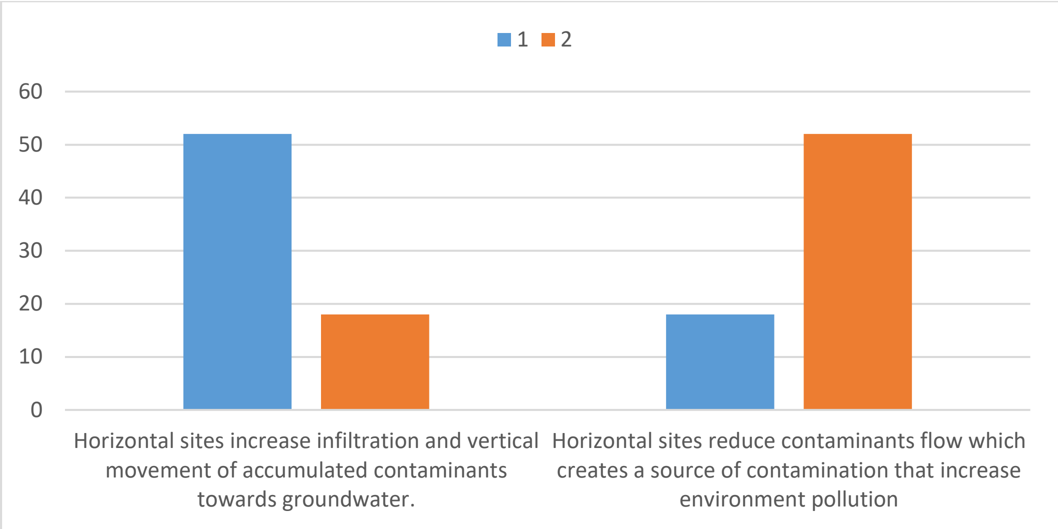

Figure 6:15 Potential hazards associated with flat site

Figure *6:16* shows that "Migration of contaminants in the direction…" ranked first by 60.42% (n= 46) participants, while ranked second by 31.57% (n=24) participants. "Spreading of contaminants…" ranked first by 31.57% (n=24) participants and second by 60.42% (n= 46) participants.

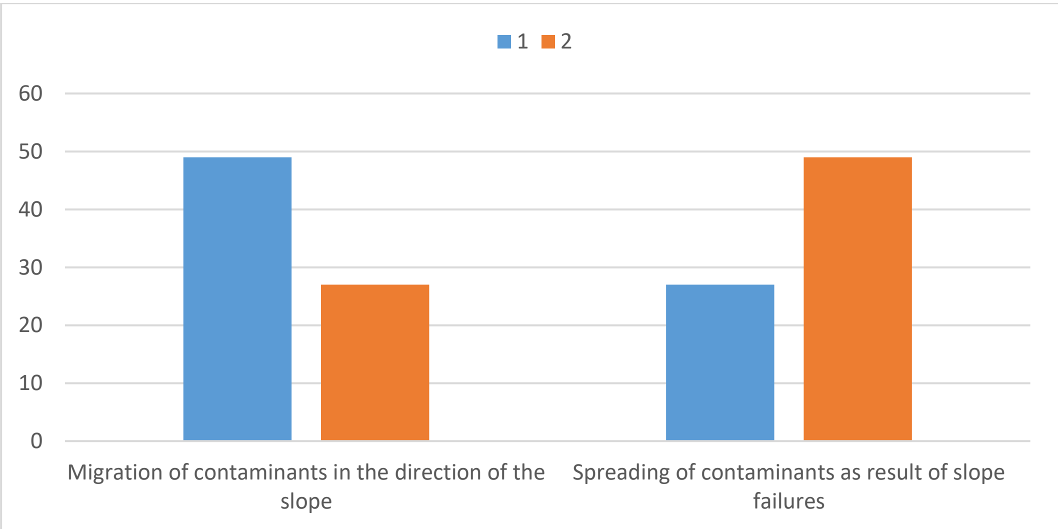

Figure 6:16 Potential hazards associated steep site

6.7.8.2 Ranking potential hazards

The VAHP analysis of potential hazards associated with site topography. Firstly, the results of flat site shows that vertical movement of accumulated contaminants due flat sites ranked first (weight of 43.334). Gurunadha Rao and Gupta (2000) indicated that horizontal sites increase infiltration and vertical movement of accumulated contaminants towards groundwater. In addition, horizontal sites may also create a source of contamination due to low movement of pollutants. This hazard ranked second (weight of 32.650) (Table 6.25). Secondly, the results of potential hazards associated with steep site show that migration of contaminants in the direction of slope, which may pose a risk to adjacent sites. This hazard ranked first (weight of 41.667). In addition, the potential of spreading of contaminants due to slope failure ranked second (weight of 34.335).

Table 6.25 The weight of the potential hazards associated with site topography

Site topography	Potential hazards	Weight	Normal	Rank
Flat site	Horizontal sites increase infiltration and vertical movement of accumulated contaminants towards groundwater	43.334	0.430	1
	Horizontal sites reduce contaminants flow which creates a source of contamination that increase environment pollution	32.650	0.570	2
Steep site	Migration of contaminants in the direction of the slope	41.667	0.548	1
	Spreading of contaminants are result of slope failure	34.335	0.451	2

6.8 Agreement on the Ranking of the Potential Hazards

SPSS 26.0 program was adopted to conduct statistical analysis. The Shapiro-Wilk test results indicated that the data collected are not normally distributed because all the *p*-values produced by the test were less than 0.05. After finding the data reliable, statistical analyses, including Kruskal-Wallis H and Kendall's *W* test were performed on the data. From the Kruskal-Wallis H test results, it could be inferred that all the differences in opinions were not statistically significant as the *p*-values of all the potential hazards were more than 0.05 (Table *6.26*). In addition, Kendall's W test was performed to calculate the coefficient of concordance. The results of the analysis show a significant degree of agreement exists among all of the participants regarding the ranking of potential hazards associated with brownfield sites. (detailed in Table 6.26).

Table 6.26 Kruskal-Wallis H and Kendall's W analysis of potential hazards associated with brownfield sites

Information	Potential hazards	Kruskal-Wallis H		Kendall's coefficient of concordance		
		X^2	*P-value*	W	X^2	*P-value*
Surrounding areas **(**Residential**)**	PH 5	5.239	0.387[a]	0.169[b]	25.658	0.000
	PH 4	0.545	0.990[a]			
Surrounding areas **(**Industrial/Commercial**)**	PH 7	5.128	0.382	0.178	26.079	0.000
	PH 6	0	0.930			
Buildings and other structures	PH 8	4.407	0.492	0.144	21.868	0.000
	PH 10	1.913	0.861			
	PH 9	3.129	0.680			
Underground services **(**Water pipes**)**	PH 13	5.387	0.371	0.300	0.041	0.026
	PH 11	3.053	0.692			
	PH 12	1.543	0.908			
	PH 14	2.134	0.830			
Underground services **(**Gas pipes**)**	PH 15	1.800	0.876	0.405	123.000	0.000
	PH 16	2.455	0.783			
	PH 18	7.328	0.197			
	PH 19	6.053	0.301			
	PH 17	2.023	0.846			
Underground services **(**Electricity cables**)**	PH 20	3.287	0.656	0.122	27.900	0.000
	PH 23	6.802	0.236.			
	PH 22	4.407	0.492			
	PH 21	4.055	0.542			
Storage of materials and old tanks	PH 25	4.610	0.465	0.117	8.895	0.003
	PH 26	4.610	0.645			
Previous mining activities	PH 28	8.329	0.139	0.522	119.103	0.000
	PH 29	4.307	0.506			
	PH 30	8.845	0.115			
	PH 27	3.994	0.550			
Invasive species (plants)	PH 34	4.780	0.443	0.648	147.742	0.000
	PH 32	3.423	0.635			
	PH 33	6.835	0.233			
Made ground	PH 38	3.423	0.635	0.438	133.021	0.000
	PH 40	2.250	0.814			
	PH 37	8.379	0.137			
	PH 39	7.057	0.216			
	PH 36	8.969	0.110			
Site topography (Steep site)	PH 53	4.668	0.458	0.284	6.368	0.000
	PH 52	4.668	0.458			
Site topography (Flat site)	PH 54	3.725	0.590	0.177	13.474	0.000
	PH 55	3.725	0.590			

6.9 Summary of Findings

As considered in the previous sections of this chapter, the quantitative analysis steps aimed to rate the necessary information to establish pollutant linkage model (survey part two) and prioritizing the potential hazards associated with brownfield sites (survey part three). This aim has been met through the application of various statistical analyses, including descriptive analysis, reliability test, normality test, Kruskal–Wallis H test, Kendall's *W*, and VAHP (described in Section 4.8.2). However, several conclusions have been drawn from the quantitative analysis, which have importance on the preliminary assessment of brownfield sites. Mainly, some professional roles have differencing views towards hazards. For instance, geophysicist, geochemists and hydrologist do not raise concerns regarding the ground movement that can be resulted from the removal of storage and tanks, while this hazard was rated important by the other professions.

This research (survey part two) shows the pollutant linkage concept is mainly used as a means to link sources, migration pathway and receptors, to get benefits from available information to best portray pollutant linkage in multiple dimensions to inform and help wide range of consultants, environmental regulators, decision-makers, construction industry and other stakeholders to present the necessary information to establish the components of the pollutant linkage model (Source-Pathway-Receptor). The summary of part two of the survey on the raking of the necessary information to establish the pollutant linkage model is shown in Figure 6:*17*. The results indicate that this information is significantly important in identifying a pollutant linkage model. It is noted that site history, made ground and previous mining activities are the most frequent information to identify the source of hazards in brownfield sites. Meanwhile, the mean scores of the importance of information to assess contaminant pathway imply that all the information has significant importance.

The findings of part three of the survey were the final step to validate the conceptual framework by prioritizing the potential hazards associated with brownfield sites that have been identified in the literature. Figure 6:*18* shows the final version of the conceptual framework for the preliminary risk assessment of brownfield sites that rates the necessary information to establish the pollutant linkage model and prioritizing the potential hazards associated with brownfield sites.

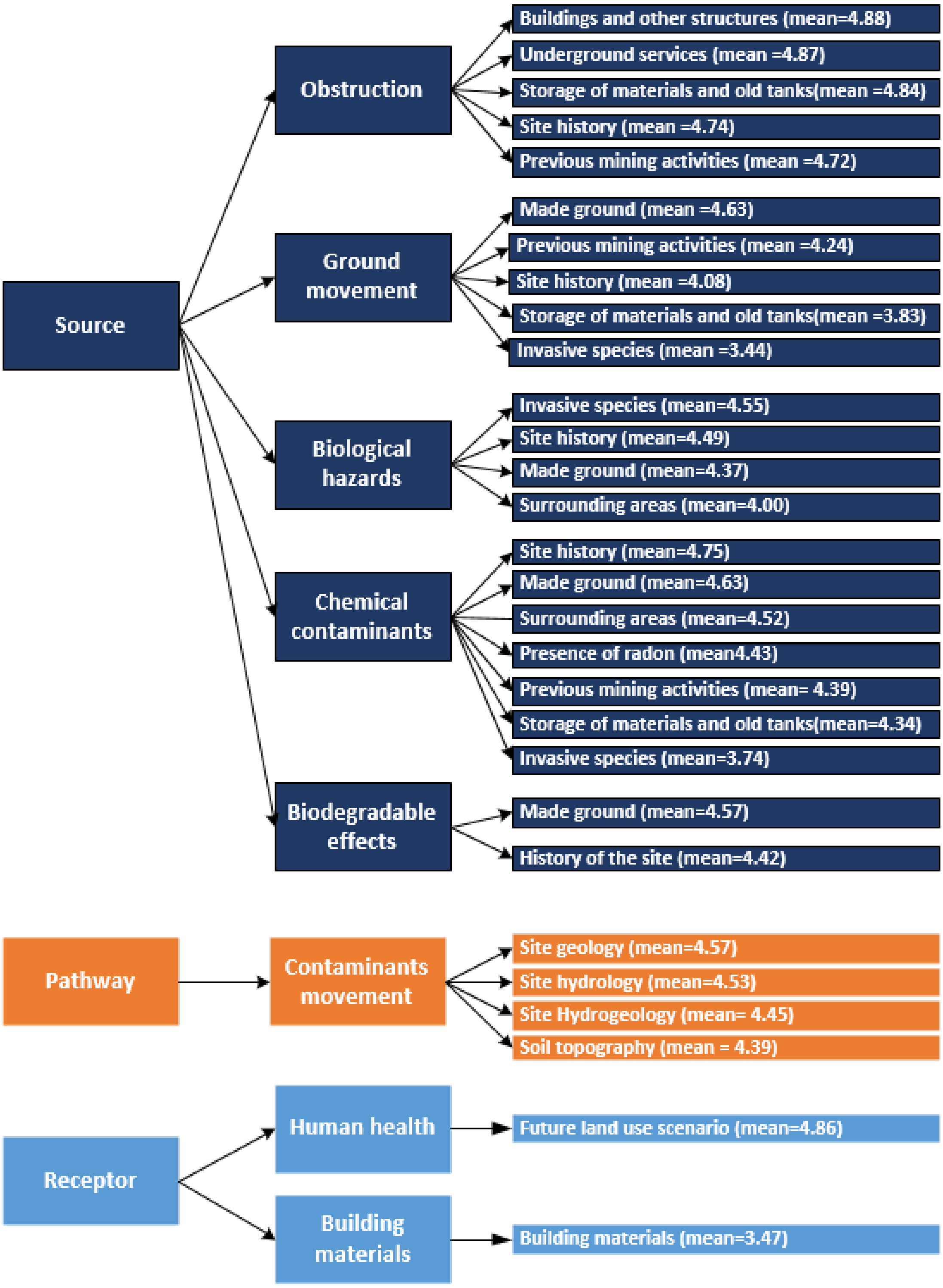

Figure 6:17 The raking of the necessary information to establish the pollutant linkage model

6.10 Comments from Participants

This section discusses the open-ended questions, where participant could provide feedback about the required information for preliminary risk assessment and potential hazards associated with brownfield sites. Many respondents reported positively on the required information. All participants answered "no" to the missing information for the initial assessment. One participant mentioned that this information provides an excellent start for initial site appraisal, others confirmed it is sufficient to make effective decisions at the initial stage. Besides, one comment mentioned that it appears to be a very good and beneficial approach overall, another participant indicated that it helps investigators focus and guides them through the various aspects that they need to take into account during the brownfield site redevelopment process. In addition, the participant highlighted the robustness between the information and the associated risks. More allowing the identification of most hazards related to brownfield sites.

Despite the positive comments, constructive criticism was provided by the respondents, for example, no clear classification of hazards during the project lifecycle which will help assessors and other stakeholders to identify hazards for a particular phase of redevelopment. Others suggest providing more details about geotechnical hazards. For example, when considering geotechnical properties, one might also consider natural cavities, e.g. swallow holes, man-made cavities from mineral extraction, groundwater level and quicksand.

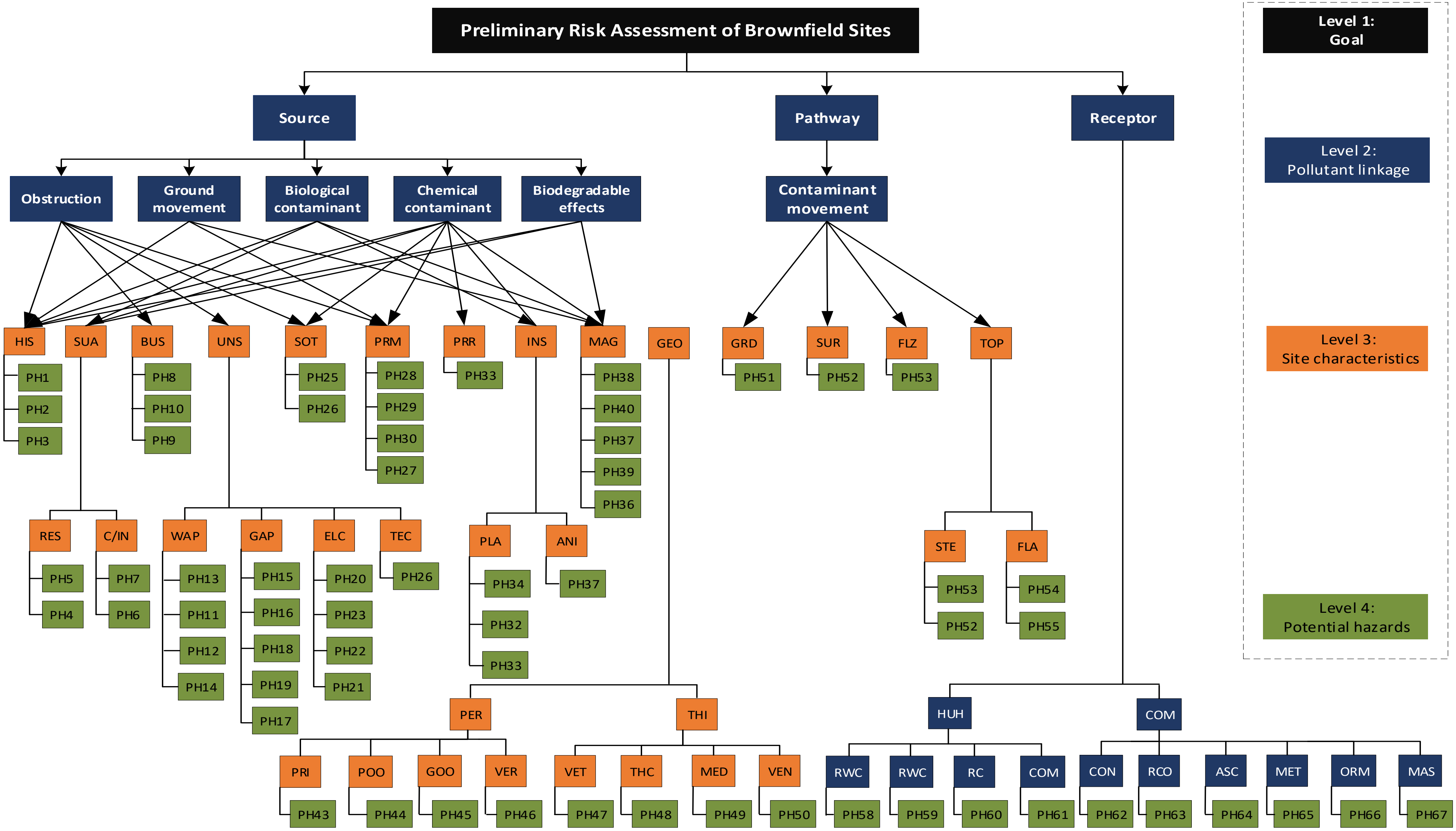

Figure 6:18 The final version of the conceptual framework for preliminary risk assessment of brownfield sites

6.11 Chapter Summary

This chapter has accomplished one of the main objectives of the study, by holistically rating the necessary information to establish a pollutant linkage model and weighting the potential hazards associated with brownfield sites. To do this, a questionnaire survey was performed with 76 brownfield experts, followed by statistical analysis and VAHP method. The data were collected via a questionnaire survey with 76 professionals with brownfield experts.

The contributions of this study to the redevelopment process of brownfield sites in at least two ways. Firstly, the resulting from this research used in conducting preliminary risk assessment of brownfield sites hone their understanding of the necessary information to establish the component of pollutant linkage model. Secondly, potential hazards resulting from this research can help industry professionals responsible for decision-making in the development of brownfield sites projects and their understanding of the likely hazards associated with brownfield sites, representing a solid starting point to conduct detailed risk assessment and remediation successfully.

The final version of the framework was discussed in detail. In the next chapter, the conceptual framework will serve as a basis for the development of the DSS. The priorities established amongst the potential hazards might help developers, planners and other stakeholders assess and develop brownfield sites with limited resources. In such situations, the priorities can be relied upon to identify and select the most appropriate combination of hazards to be investigated in the next stage of risk assessment.

7. CHAPTER 7: DECISION SUPPORT SYSTEM DESIGN AND VALIDATION

7.1 Introduction

Utilising the information reported in the previous chapter, a decision support system (DSS) for Preliminary Risk Assessment of Brownfield Sites (PRAofBS) has been developed. The architecture of the tool is explained in Section 7.2, while Section 7.3 demonstrates the functions of the tool. Section 7.4 includes three main sections, the first section provides the reader with data collection procedures and provides an overview of the survey structure. It also introduces the different methods adopted in the analysis of the obtained data of the online survey. The second section presents a quantitative approach to validate the tool in terms of graphical user interface (GUI), ease of use, plus the level and quality of information presented in the tool. The third section presents a verification exercise (qualitative approach), where the preliminary of information for two case studies were entered into the system, the outputs are then compared with the results and interpretative reports. Finally, Section 7.5 presents a summary of the chapter.

7.2 Architecture of the Decision Support System

The DSS for this study has been developed as a web–based tool to enhance its accessibility and to enable it to be disseminated to users. The main purpose of the DSS is the preliminary assessment of brownfield sites.

A Web–based DSS conforming to a layered software architecture can be implemented as a traditional monolithic and proprietary system (Silva, Roque and Almeida, 2006). Monolithic architecture is a traditional way of building applications. Monolith means composed all in one piece. Generally, such a solution comprises a client–side user interface, a server–side–application, and a database. It is unified, and all the functions are managed and layered in one place (Jayashree and Selvakumar, 2020). Common layers are the presentation, application logic, business logic, Data Access Object (DAO) and related code that interacts with the database files or another source (Figure *7*:*1*).

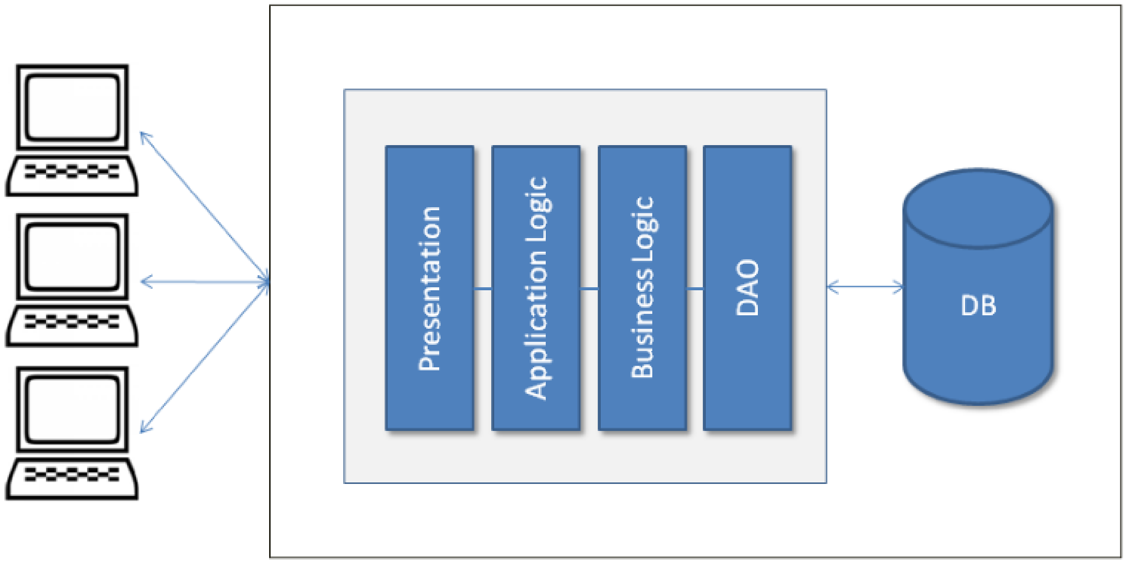

Figure 7:1 Monolithic architecture of the DSS
Source: Sharma (2017), reused with permission from Sonal Shetty @Packt Publisher

The following section provides an explanation of the components within monolithic architecture: (i) presentation; (ii) application logic; (iii) business logic; (iv) data access logic; and (v) database.

Presentation

The presentation is called front–end and is part of a website that users interact with directly. It is also referred to as the 'client–side' of the application. It includes everything that users experience directly: text colours and styles, images, graphs and tables, buttons, colours and navigation menu. HTML, Javascript and CSS are the languages used for front end development (MacIntyre *et al.*, 2011). For instance, a simply structured webpage is represented in HTML code in Figure *7:2*.

```
<!DOCTYPE html>
<html lang="en">
<head>
    <meta charset="UTF-8">
    <meta name="viewport" content="width=device-width, initial-scale=1.0">
    <title>PRAoBA</title>
</head>
<body>

   <h1>Hello World !</h1>

</body>
</html>
```

Figure 7:2 HTML webpage (created by the author)

HTML code can be opened in any internet web browser, such as Chrome, Mozilla Firefox, Opera, Microsoft Edge or Microsoft IE, and Figure 7:3 is a simple HTML example.

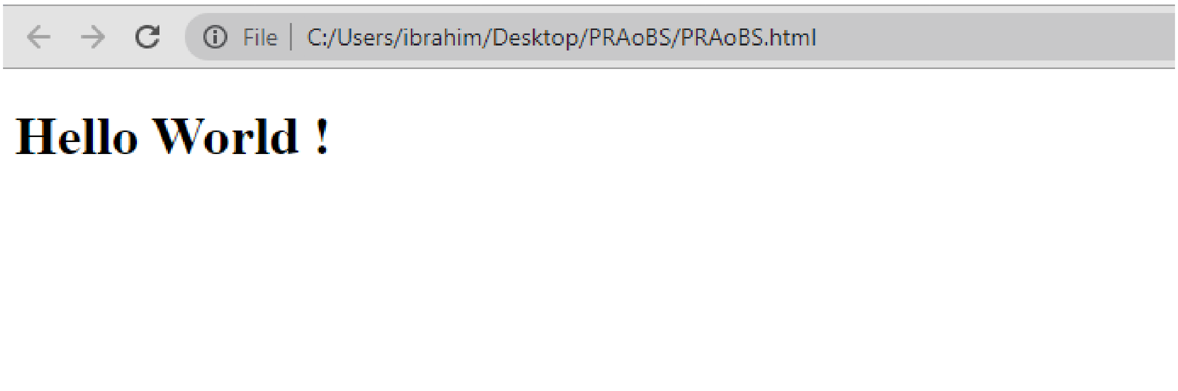

Figure 7:3 A simple HTML file (created by the author)

Application Logic

Application Logic is mostly workflow logic. It is the application specific coordination of domain and infrastructure components according to the requirements of that particular application (Bourne, 2014).

Business Logic

The business logic layer is mainly based on the user's request parameters, it refers to the logic and algorithms serving as the foundation of code in business software (Gao, 2018). This comprises the set of components responsible for processing data received from the presentation layer. It stores and arranges data and also makes sure everything on the client–side of the website works fine. It is the part of the website that you cannot see and interact with and it is implemented in this study by a simple powerful language designed (PHP) for creating HTML (Hyper Text Markup Language) (MacIntyre *et al.*, 2011). For instance, a simple PHP code is presented in Figure 7:*4*.

```
}
.menu {
    background-color: rgb(101, 101, 206);
    text-align: left;
    margin: auto;
    padding: 10px;
}
.Home_image {
    position: relative;
    text-align: center;
    color: white;
  }
  .section {
      font-size: 24px;
      font-weight: bold;
      color: black;
  }
```

Figure 7:4 A simple PHP code (created by the author)

Data Access Object

The Data Access Object (DAO) pattern encapsulates underlying details of DB manipulation from the business logic layer. It is basically an object or an interface that provides access to an underlying database or any other persistence storage (Kramer and Newcomb, 2010). The business component that relies on the DAO uses the more straightforward interface exposed by the DAO for its clients. All details of storage are hidden from the rest of the application by the DAO. Thus, this pattern allows the DAO to adapt to different storage schemes without affecting its clients or business components. Essentially, the DAO acts as an adapter between the component and the data source (Berger, 2005).

Database

The database is essential for any website development and choosing which database is one of the main requirements for website architecture. The components include a database for storing, managing and/or retrieving information for management decision support. According to Liu (2020), PostgreSQL was ranked as one of the most popular database

management systems worldwide, with a ranking score of 552.23 (DB-ENGINES, 2019). Therefore, the PostgreSQL database management system has been adopted for this study.
In PostgreSQL, all domain and application data are managed and organised through a central database. The main advantages of using PostgreSQL databases are (Krosing and Mlodgenski, 2013):

1- They allow for quick data reading and writing
2- They support mass storage
3- Free and open–source
4- They are easy to expand
5- They provide accurate and consistent results based on their data.

The DSS data was stored as relational tables, which is a theoretical model of database systems that provide a means of representing data, the relationships between data items, and the way(s) in which the data may be used. Figure 7:5 shows the relationship between the tables in the database, which includes six tables as detailed below:

–*Site_ information:* for storing site information for preliminary risk assessment, including attributes:

- *category*: the name of the main information
- *subcategory*: the name of the sub information
- *text:* description of the main formation
- *view_type:* site information was categorised into source, pathway and receptor to develop pollutant linkage model.

–*Potential_hazards:* for storing potential hazards associated with brownfield sites, including attributes:

- *Hazards:* the indicator of the hazards
- *Chart pie:* showing the weight of hazards as calculated by the VAHP mode
- *Text:* description of the hazards

–*User:* this is a table used by site admin only to manage the DSS website.

- *email: storing the email of the admin*
- *encrypted_password:*
- *remember_created_at:* is used to save the login credentials of the user who is currently logged in.
- *reset_password_sent_at:* send reset password instructions by email.
- *reset_passowrd_token:*

–Assessment:

- *report_data: string the output of the preliminary risk assessment*

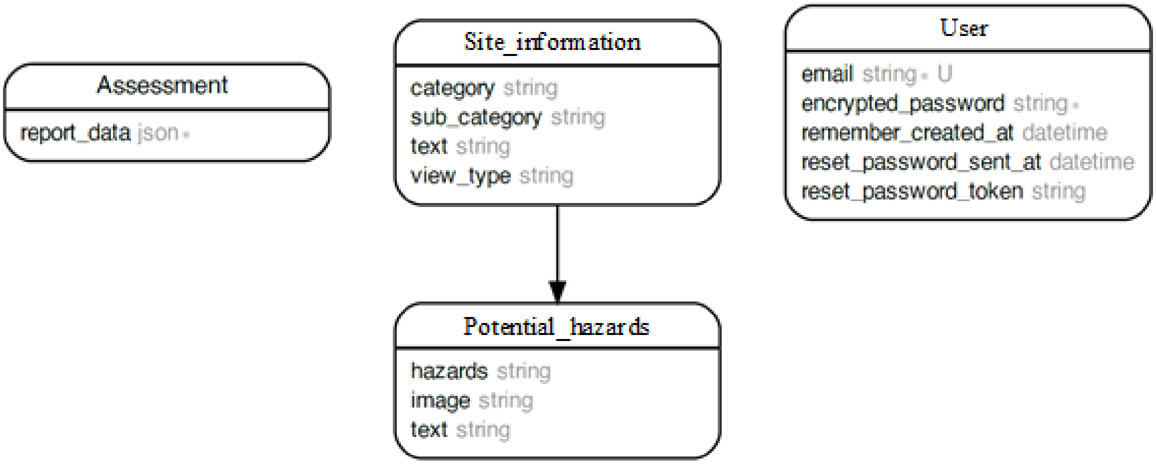

Figure 7:5 The relationship between tables in a DSS database

7.3 Demonstration of the DSS Tool

The DSS tool in this study has been developed based on the technologies and tools described in Section 7.2. All the potential hazards associated with brownfield sited developed are structured and stored in the DSS database. Through the DSS, assessors are requested to provide site information to identify potential brownfield site hazards. The potential hazards are prioritized in terms of their likelihood of occurrence in brownfield sites. The DSS can be accessed online via http://PRAOFBS.herokuapp.com.

Welcome page

The welcome page of the DSS tool presents the main aim of the tool. The decision support process begins by clicking on the “Start your assessment” button. The components of the welcome page are presented in Figure 7:6 as follow:

- A1: the DSS menu includes:
  - Home: reload the page
  - New Assessment: to start a new assessment
  - Login: allows the user to manage the main page (Figure 7:9)
- A2: introduction to the aim of the tool.
- A3: to start the preliminary risk assessment of the given brownfield site.

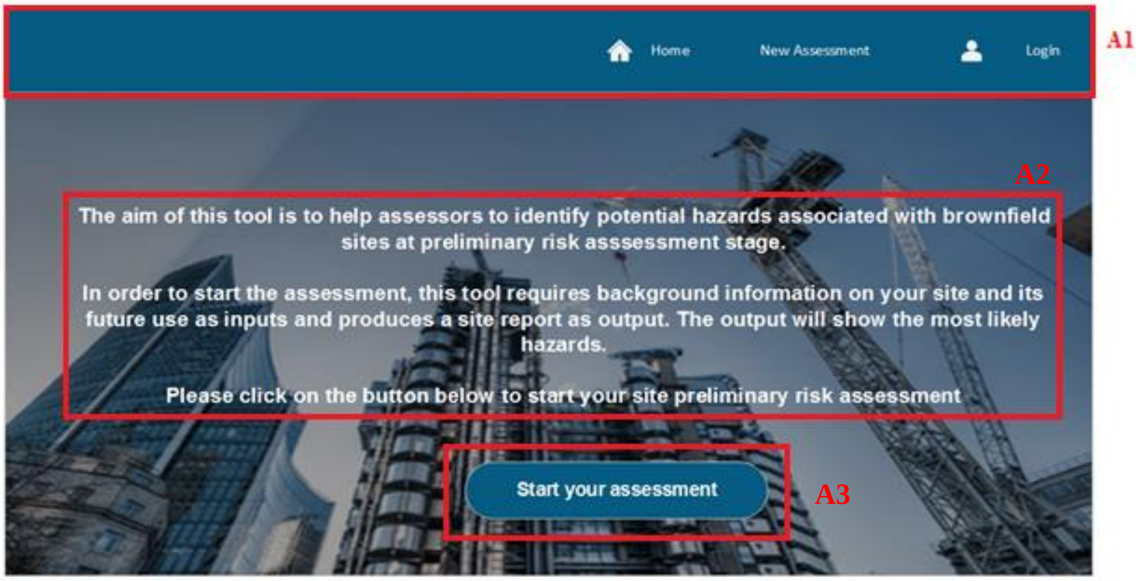

Figure 7:6 Welcome page of the preliminary risk assessment of the decision support system

Preliminary risk assessment

Preliminary risk assessment can be carried out on this page (Figure 7:*7*). The details of the page are presented as follow:

- B1: input form for preliminary risk assessment of brownfield site. The user is required to select the right information to the given site.
- B2: Generate report button is provided at the end of the form to generate the outputs.

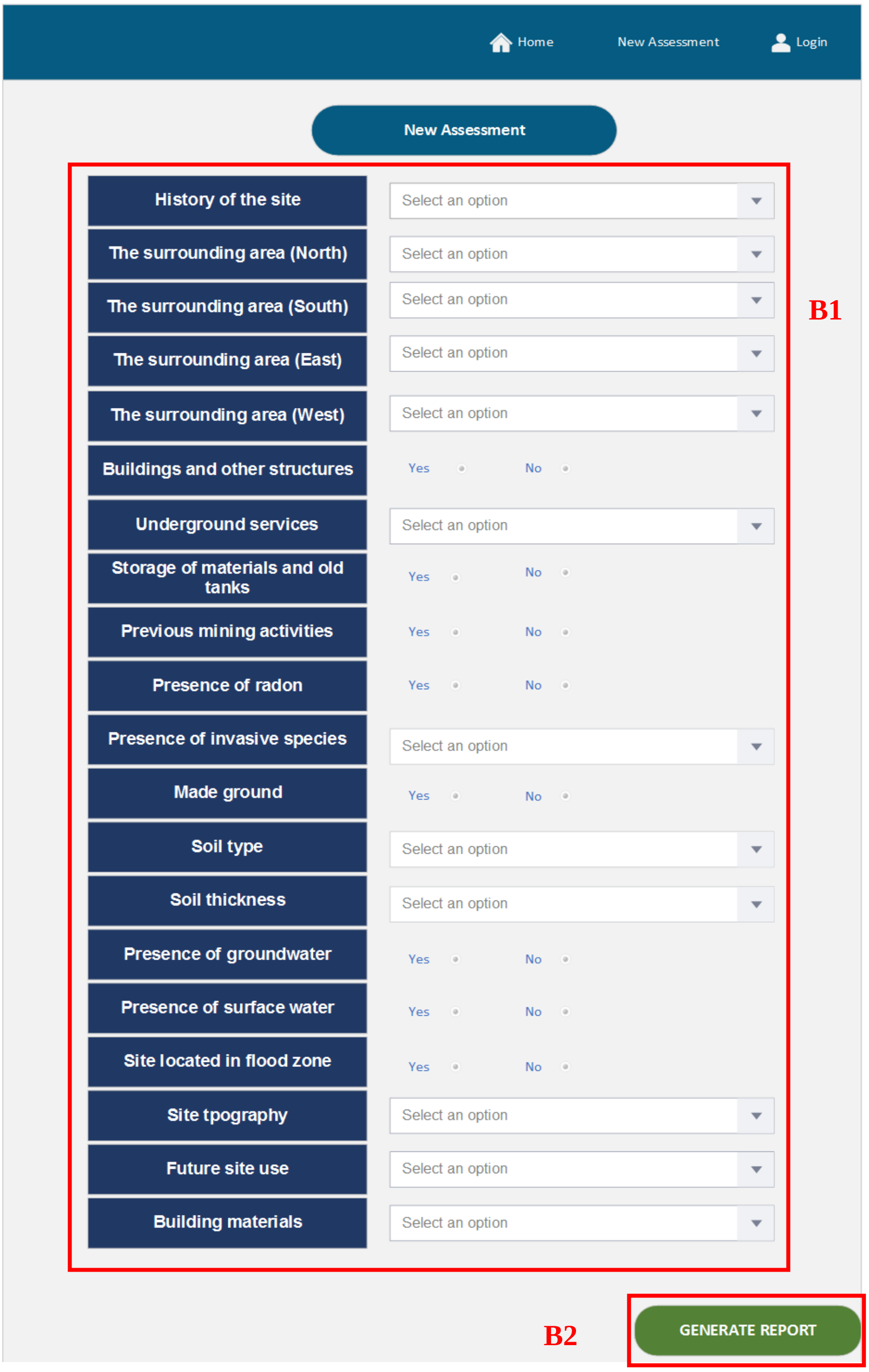

Figure 7:7 The main page of the preliminary risk assessment of the DSS

The outcomes of the potential hazards associated with brownfield site are illustrated in

Figure 7:8, which includes:

- C1: shows the type of information selected by the users based on the pollutant linkage model.
- C2: the information selected by the user. The user can here click on the information and see the potential hazards as presented in section C4 and C5.

- C3: the information selected by the user
- C4: this section provides users with helpful advice relating to the information they have selected, including an indication of the potential hazards they may consider when they redevelop the given brownfield site.
- C5: the chart pie in the output page shows the rank of the potential hazards.

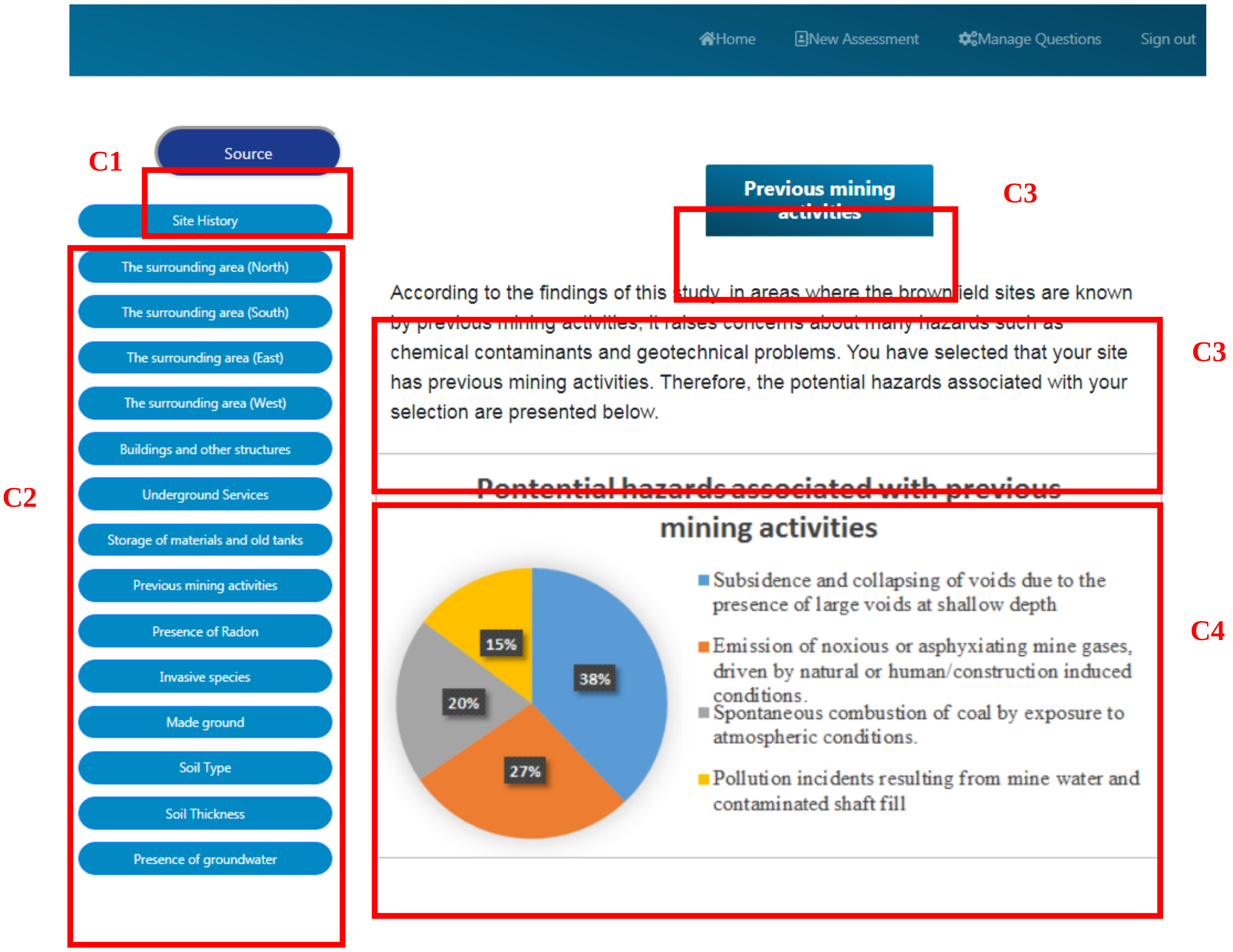

Figure 7:8 Output of the preliminary risk assessment of the DSS

The administration of the page can manage the main page of the DSS after logging in the account (shown in A1); whereby, it can update the information and associated hazards as illustrated in Figure 7:9. The administration can manage the main page as follow:

- E1: add information
- E2: Present general description about the information
- E3: clicking on the button to download the rank of the potential hazards
- E4: By clicking on this button, the information will be updated.

- E5: by clicking on this button, the admin can add a new information.

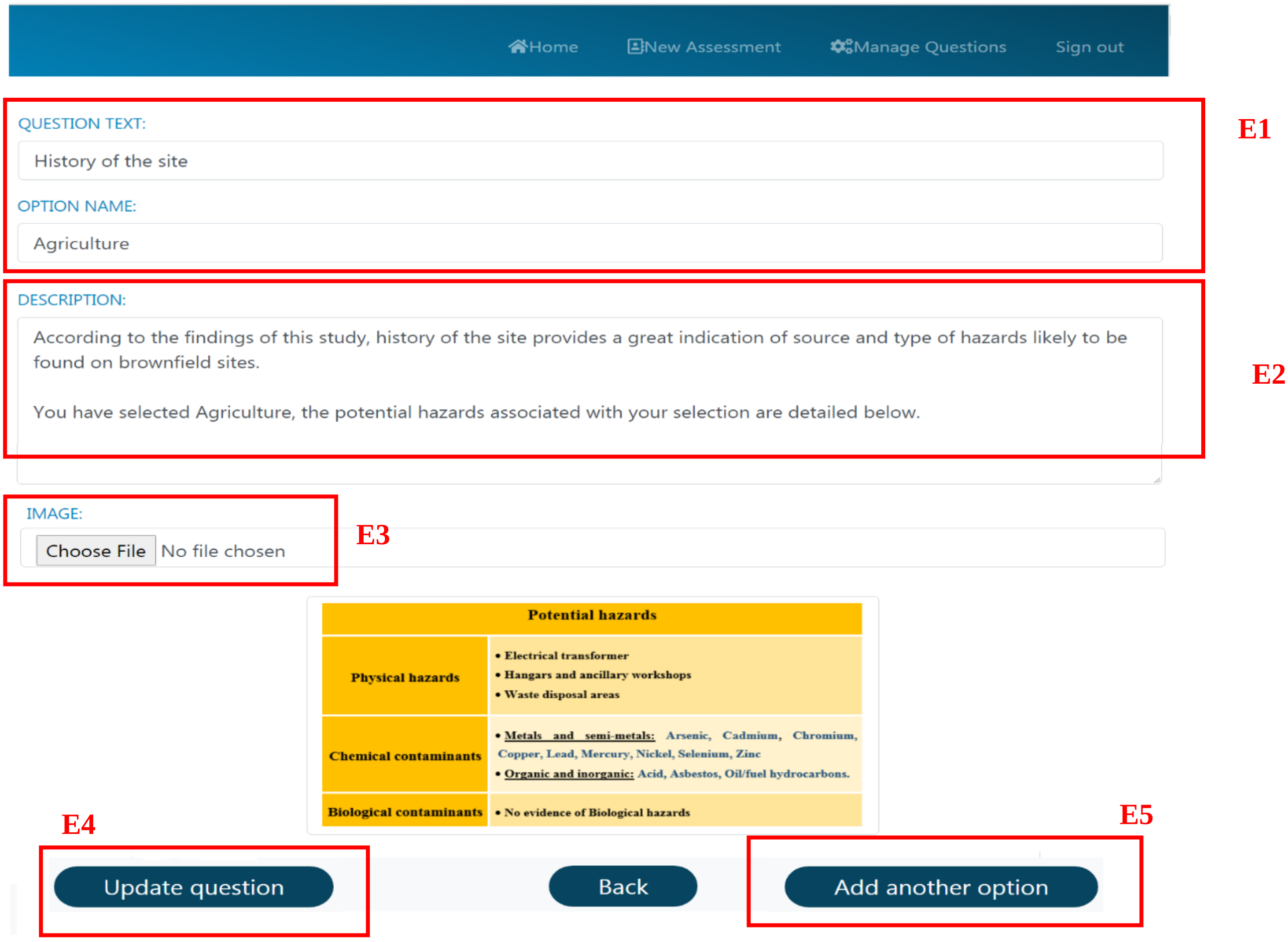

Figure 7:9 Manage the main page

7.4 Validation Process of the Decision Support System

The validation of the DSS online tool was conducted at the final stage of the tool development to garner comments and to measure how well the Tool was seen to meet the intended target of the research that will enable the researcher to get feedback to validate the tool, which in future could have practical application. The validation of the DSS tool, facilitated by two methods, firstly an online questionnaire (detailed in APPENDIX II: PRAoBS DSS Tool Validation Survey) was designed and uploaded to the internet and named a domain name, **PRAofBS.herokuapp.com** to determine whether the tool has met with users' requirements and expectations in terms of: (i) its graphical user interface; (ii) the effect of the tool to the user in applying preliminary risk assessment for brownfield sites; (ii) the level of information provided by the tool; (v) how likely the user will use the tool again or recommend it. All constructive comments received will be used to improve the Tool in future work. It is important to indicate that ethical considerations were also considered in the validation of the **PRAofBS** Tool, and before starting the questionnaire, participants were asked to sign the consent form. Secondly, the validation was also carried out by functional testing, which involved testing tool inputs and outputs against two real–life case studies to check the accuracy of data outputs. Figure 7:*10* presents an overview of the DSS validation process.

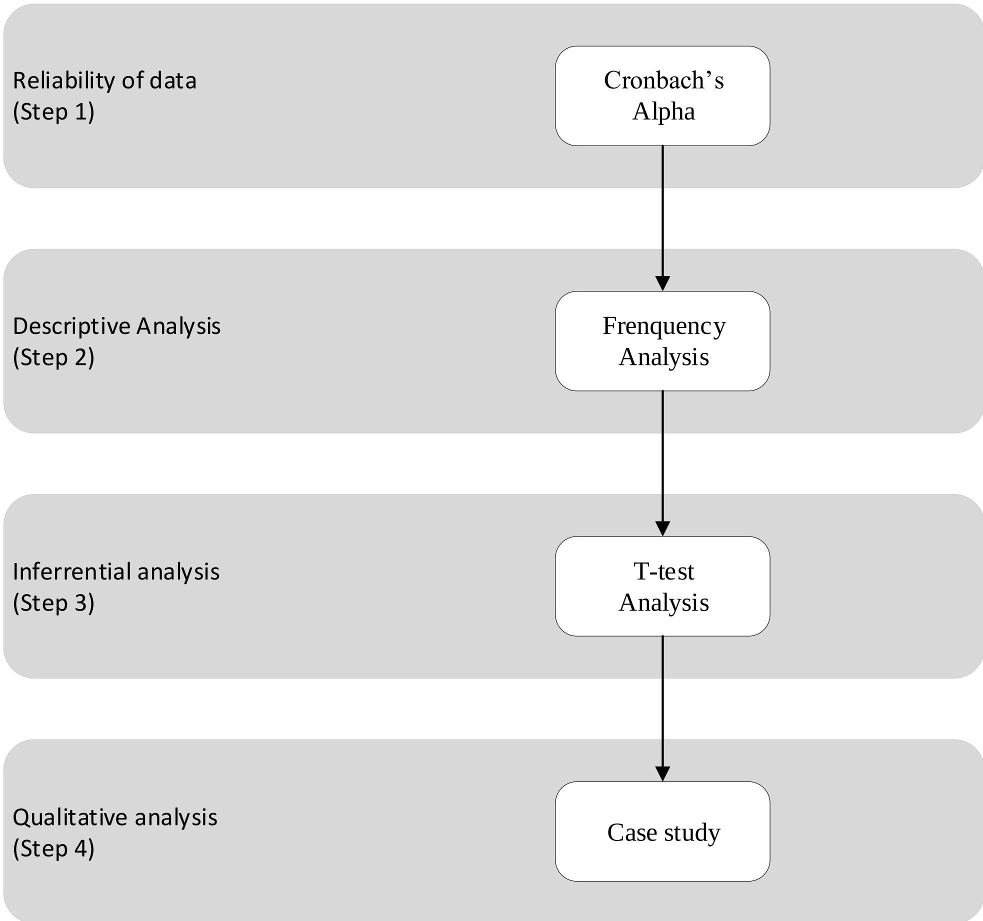

Figure 7:10 The validation process of the decision support system

7.4.1 Quantitative Validation of the PRAofBS Tool

This section provides insights into the quantitative validation of the PRAofBS tool.

7.4.1.1 The Reliability of Questionnaire Data

Following the same approaches used earlier in the study (Section ??? – framework validation), the reliability of the data collected in this second survey was also considered by determining the Cronbach's alpha. As shown in Table *7.1*, there is a strong internal consistency (i.e. >0.70 as explained in Section 4.8.2.1).

Table 7.1 The reliability of the survey data tested using Cronbach's Alpha

Reliability Statistics	
Cronbach's Alpha	N of Items
0.76	5

7.4.1.2 Demographics of the Participants

Unlike the previous survey, participants were not required to be experts. However, participants were required to have some level of experience in brownfield site management. Figure 7:*11* shows that 53.8% (n=28) of participants have experience >5 years in the management of brownfield sites, 34.6% (n=18) have experience 3–5 years and 11.5% (n=6) have experience <3 years.

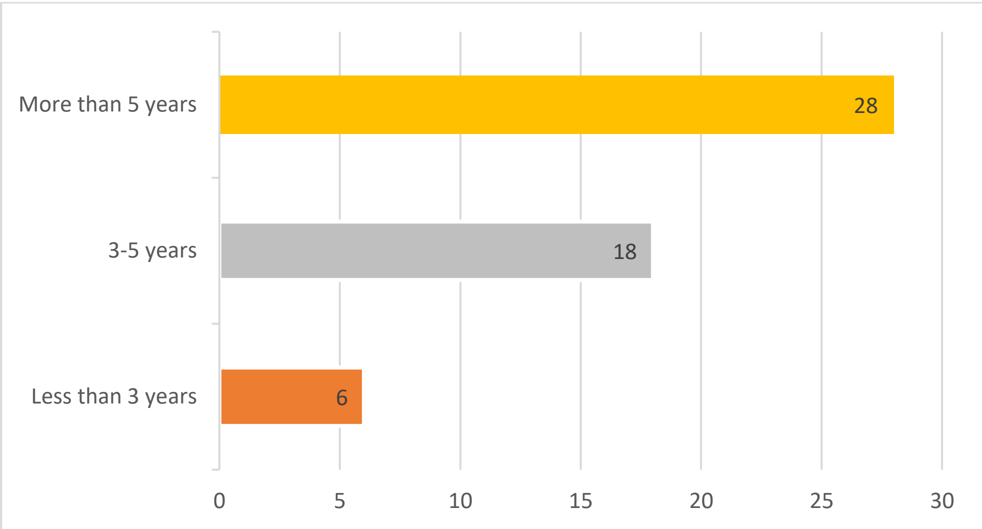

Figure 7:11 Distribution of participant's experiences in brownfield site management

Besides experience it is important to also identify the current roles of the participants to check they are suitable to answer the survey questions. The highest number of responses, 21.2% (n=11) identified as Geo–environmental engineers, whom play a critical role in the investigation of brownfield sites. Geotechnical engineers accounted 15.4 % (n=8) of participants, followed by 13.5 % (n=7) were Planning officers, and 11.5% (n=6) were Brownfield project managers, 11.5% (n=6) were Environmental advisors and 11.5% (n=6) were Safety managers; whilst Geologists and Hydrologists represented 9.6% (n=5) and 5.8% (n=3) of the participants, respectively (Figure *7:12*).

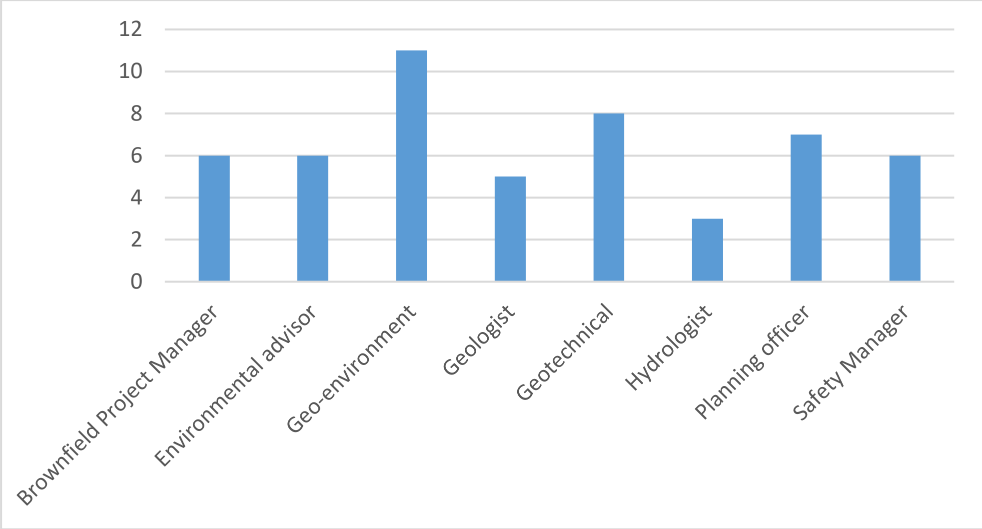

Figure 7:12 The professions of participants involved in the survey.

7.4.1.3 Validation Criteria

7.4.1.3.1 The graphical user interface (GUI)

According to Cohen and Wang (2014), since its emergence in the 1980s, the graphical user interface concept has become a crucial factor in determining the success of systems and applications on the market. A good GUI plays an essential role in enhancing the interaction between the user and the tool, which will lead to the success of the device. Hu *et al*. (1999) argue that GUI's are important because it is where knowledge and information are visualised and represented and communicated between users. Therefore, this factor is considered when validating the usefulness of the DSS tool.

To validate the GUI of the DSS, participants were asked to provide their impressions of the DSS Online Tool. Descriptive statistics for GUI of the DSS was analysed in detail in SPSS based on the information that was collected by the questionnaire. The frequency presented in Figure *7*:*13* showed that the majority of the participants were impressed with the GUI of the tool, with over half rating it as "Excellent or Good" (51.9%), some rated it as "Average" (26.9%) or "Poor" (21.2%) and nobody considered it "Terrible".

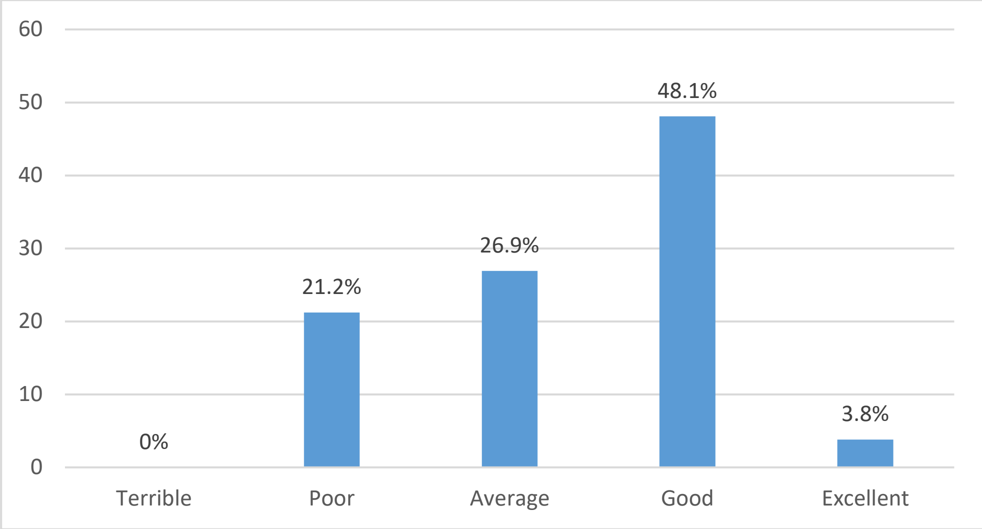

Figure 7:13 Participate impressions of the DSS Graphical User Interface (GUI)

The questionnaire survey classified the participants into three main groups based on their experience in developing and managing brownfield sites. According to SPSS, the question received mean = 3.34 (SD =0.860; n=52) and the results of the mean for each group are also shown in Table *7.2*. T–tests were conducted to measure the significance of the means (as described in Section 4.8.2.3.5), if the p–value was >0.05 this means that there is no significant difference between the members of the three groups. It can be seen from Table *7.2*, that the p–value is <0.05 (n=??), which means any differences between the groups (participants with experience <3 years and participants with experience >5 years) are significant. This could be due to the fact that the more experienced participants may have used other, already available, commercial tools in the industry that have of course more sophisticated graphic presentations than the tool developed in this study, given that this is a research tool prototype that was created with limited resources and time. However, an overall mean of 3.34 (SD =0.860; n=52) (Table 7.2) is considered applaudable (as outlined in Section 4.8.1.3), but still indicates further work may be necessary to make it more desirable to users. This is further supported by participant feedback recommending the graphics are improved to enhance user experience.

7.4.1.3.2 Ease of use and clarity

According to Thomas–Alvarez and Mahdjoubi (2013), ease of use is an essential parameter that should be highlighted when designing prototypes, applications or software in general. Therefore, the ease use of the tool was validated in terms of the entire overall process. Participants were asked whether they found the selection of criteria within the device to be difficult or easy. Figure *7:14* shows most participants reported that the DSS was easy to use (~80% saying it is extremely easy or somewhat easy).

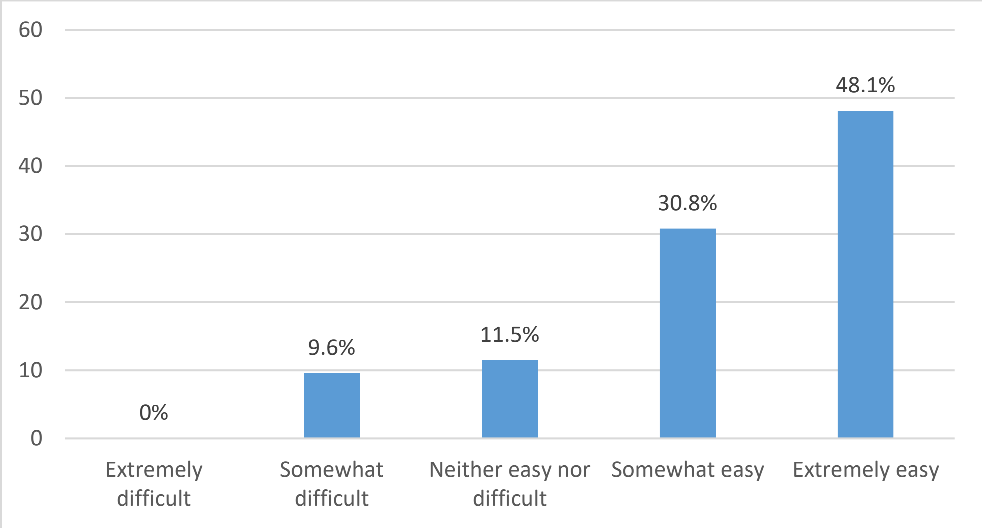

Figure 7:14 Participant responses to the ease/difficultly using the tool

Table 7.2 shows that the overall mean of participants was 4.17 (SD=0.981; n=52), which is considerably high (outlined in Section 4.8.1.3). Besides, from the results of *t*–test, the difference was not considered statistically significant since the *p*–value was <0.05 (n=52). Therefore, the use of the DSS, in terms of the overall process, was generally found to be easy, as a consequence of a high number of evaluators commenting positively on the DSS in this research, it seems reasonable to expect that the tool has the potential to be disseminated to the different stakeholders in the development of brownfield sites.

Moreover, participants were also asked to assess how the DSS Tool was clear to understand, this question was to measure how successful the tool's approach was in guiding the user in identifying the potential hazards associated with brownfield site in the early stage of the risk assessment process, and the amount of ambiguity the users faced (Figure *7:15*). The majority stated that they considered it extremely/somewhat clear (78.8%) and a low proportion believing it unclear. This question can be considered a continuation of the previous question about the ease of use of the tool and could be one reason why participants thought the device was easy because it was clear. This can be seen from the overall mean of 4.03 (SD=0.739; n=52) that this question received from the participants, as shown in Table *7.2*.

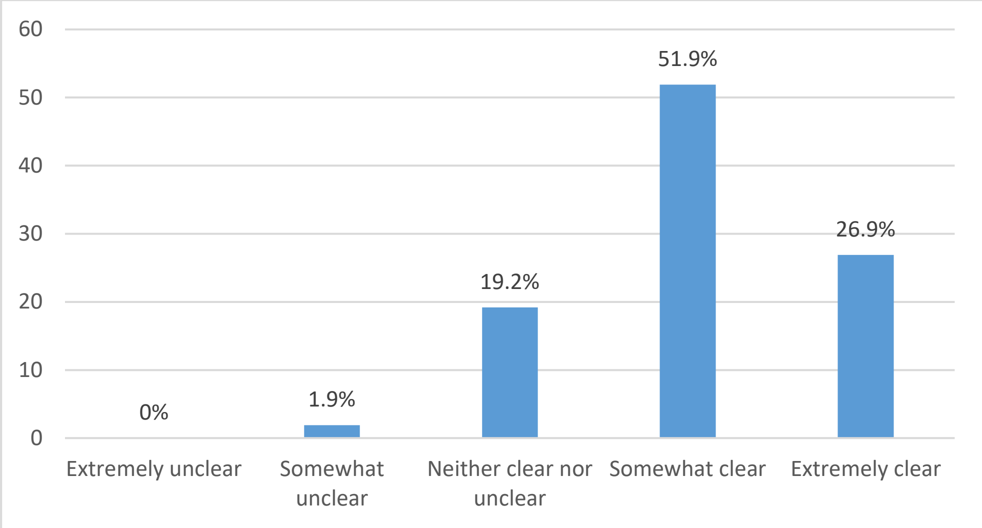

Figure 7:15 Participant responses to the clarity of the DSS Tool

7.4.1.3.3 Quality of information provided

Quality of information is a purposeful target that is expected to be met in any study. In general, it is essential that the most relevant sources of information are reviewed, and the most appropriate domain experts are consulted (Martin and Toll, 2006). In the context of designing software or applications, the appraisal of the quality of information presented, it is important to find out the usefulness of the tool (Thomas–Alvarez and Mahdjoubi, 2013). However, to validate the quality of information, participants were asked to rate the quality of the information presented by the tool. The outputs presented in Figure *7:16* shows that half the participants found the quality of information to be "Extremely/Very useful" (57.7%) and nobody claimed it "Not to be useful".

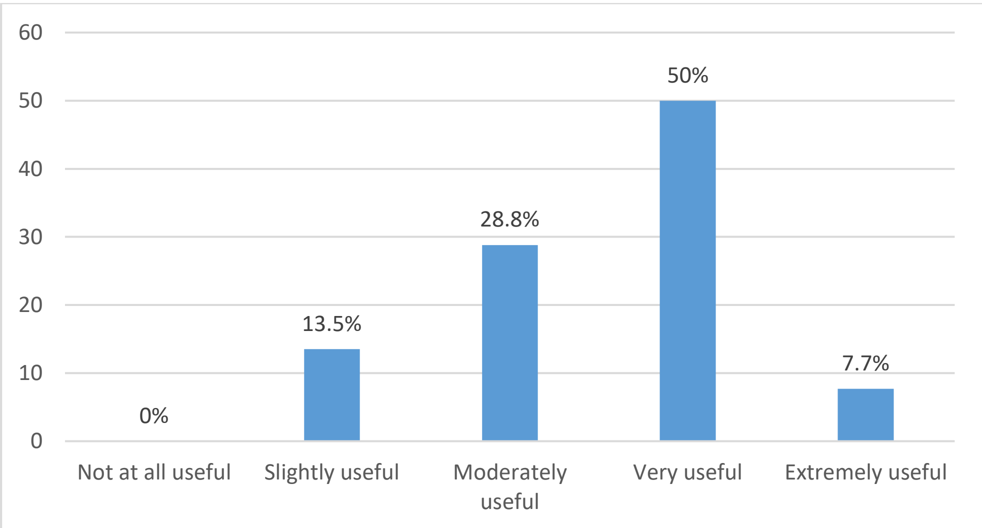

Figure 7:16 Quality of information provided by the Tool

Experience in this question plays a role in answering where highly experienced participants may have a better understanding of hazards associated with brownfield sites. The overall mean of the answers to this question was 3.51 (SD=0.828; n=52). Table *7.2* shows the difference between the means of the three groups and significance. Based on the outcomes of this question, the quality of information provided by the DSS has been confirmed as generally positive. Therefore, the tool is expected to provide different stakeholders with useful information due to brownfield sites' hazards.

7.4.1.3.4 Level of information presented in the tool

Along with quality of information provided by the tool, appropriate level of information is also highlighted as an essential feature. “Level of information” refers to how adequate information is presented in the device and organised. To validate this feature, participants were asked to what extent does the information provided by the tool allows the users to identify hazards in brownfield sites in the initial stage. Figure *7:17* shows that participants considered the level of information either “Excellent” (11.5%) or “Good” (51.9%), while 25% found it “Average” and only 11.5% rated it “Poor”. None of the respondents considered the level of information to be “Terrible”.

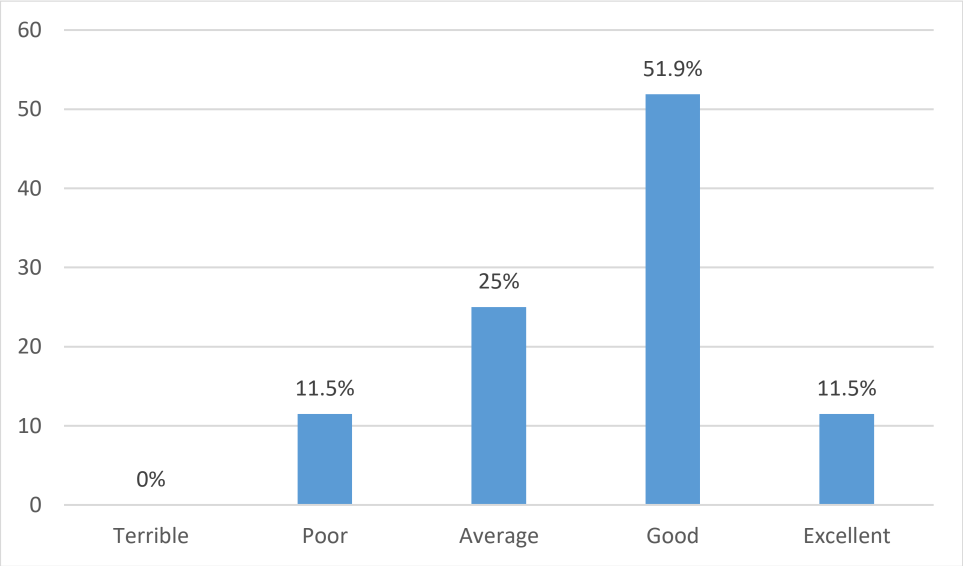

Figure 7:17 Level of information presented in the tool

This question was given an overall mean equal to 3.63 (SD = 0.840; n=52), the mean for each group is also shown in Table *7.2*. T–test was conducted to measure the significance of the means. Table *7.2* shows that the significance level higher than 0.05, which means that the difference between the groups is not significant. Therefore, the tool's level of information is comprehensive and adequate for those involved with brownfield development to have a better site assessment.

7.4.1.3.5 Recommending the DSS Tool

In general, it is inferred that the tool created in this study is a useful device that will help investigators in their preliminary risk assessment, and improve the communication between the developers, local authorities, consultancies and clients. Therefore, participants were asked if they would recommend the device for preliminary risk assessment of brownfield sites. An overwhelming majority of participants (76.9%) stated that they would recommend the DSS Tool for the purpose it has been designed. This level of support is similar to other doctoral studies where frameworks, models or tools have been developed (Lam, Mahdjoubi and Mason, 2017; Dwairi, 2019). Comments from participants that would or would not recommend the tool will be discussed in the next section, in addition to any other comments on how to improve the device.

Table 7.2 Summary of the survey results on the validation of the DSS Tool

Validation criteria	All respondents		Less than 3 years		3–5 years		More than 5 years		Diff. (A–B)	p–value	Diff. (A–C)	p–value	Diff. (C–B)	p–value
	Mean	SD	Mean	SD	Mean	SD	Mean	SD						
Graphical user interface (GUI)	3.34	0.860	3.50	0.836	3.33	0.443	3.32	0.772	0.166	0.176	0.178	0.939	0.01	0.026
Clarity of the tool	4.03	0.739	4.50	0.547	3.88	0.832	4.03	0.692	0.611	0.297	0.464	0.706	–0.146	0.077
Ease use of the entire process of the tool	4.17	0.984	4.83	0.405	4.05	0.589	4.10	0.831	0.777	0.01	0.726	0.112	–0.051	0.022
Quality of information	3.51	0.828	4.16	0.752	3.22	0.808	3.57	0.790	0.944	0.477	0.595	0.568	–0.349	0.817
Level of information	3.63	0.840	4.33	0.516	3.72	0.958	3.42	0.741	0.611	0.133	0.904	0.144	0.293	0.299

Note: SD=Standard deviation; The one sample t–test result is significant at the 0.05 significance level (p–value<0.05); Diff. (A–B)=Difference in mean scores from participants with less than 3 years and participants with experience 3–5 years; Diff. (A–C)=difference in mean score from participants with less than 3 years and participants more than 5 years; Diff.(B–C) difference in mean score from participants with 3–5 years and participants more than 5 years.

7.4.1.3.6 Feedback from participants

At the end of the questionnaire respondents were invited to include any further comments they wanted to add that may improve the DSS Tool. Therefore, this section briefly reflects on the feedback the participants proffered.

Many comments reported favourably on the benefits of the tool, suggesting it provides a strong website for preliminary brownfield site investigations for decision–makers with limited experience, allowing them to identify and prioritise potential hazards associated with brownfield sites, particularly at the initial stage of the process. The tool's innovation was also reiterated by the participant in terms of the need for such a tool in the sector of brownfield sites management. However, moving the DSS Tool forward, it was recommended to develop the tool as a part of an online forum where users can exchange information and share knowledge. As already mentioned in the main survey responses, participants also suggested improving the tool in terms of the presentation of the information and outputs. That said, others suggested that the output results should be generated in PDF format, to enable investigators to share the findings with different stakeholders. Other recommendations were that the tool needed to be more interactive, as this would increase its chances of commercialisation . It was also proposed to provide a recommendation section in the tool to suggest hazards, which could extend the overall scope of the database.

Besides the positive feedback, the DSS Tool failed to meet with the expectations of some participants. For instance, one participant mentioned that the information included is too generic; another participant expected to find incorporate graphics and supporting images to explain hazards rather than texts; another participant was disappointed not to be able to click on a pie–chart to learn more about the hazards highlighted by the tool – this participant claimed to be unsure how to use the weighting percentages generated. Therefore, clarity of instructions and a review of presentation/outputs could be the next steps in the development of the DSS Tool.

7.4.2 Qualitative Validation of the PRAofBS Tool

It is fundamentally important to be confident that the outputs of the DSS Tool are accurate and realistic. This meant running through real–life case studies with known results and comparing the performance of the DSS Tool against the expert judgements from existing/known case studies. To support this approach, an anonymous engineering consulting company was contacted and requested to provide data from previous projects they had been involved in. Case study reports were provided for two sites, which included data related to preliminary site investigation, contamination test results and interpretative statements.

Case study one : Redevelopment of a brownfield site to domestic residential

The first case study run through the DSS Tool is a preliminary risk assessment for a brownfield site converted to domestic residences. The purpose of the report was to investigate ground conditions, assess the contamination status, and identify possible receptor(s) and their vulnerability in compliance with the UK's contaminated land regime requirements. The brownfield site to be developed covers approximately 2.21Ha and lies to the east of the glassworks, covering an area of around 9.67Ha. It comprises an existing administration building to the southwest, vehicular access/weighbridges and a site office to the south, a staff and visitor carpark covering most of the proposed development, and a storage area to the north. To the north of the site is a triangular shaped open space partly used to store glass, with smaller regions covered with overgrown vegetation. The surface is predominantly compacted earth, with some areas containing compacted aggregate. The overall topography of the site gently slopes in a north/north–east direction. Further case study information is surmised in Table 7.3.

Table 7.3 Preliminary site information for case study one

Case study 1	Preliminary information
Site history	1892–1894 Mining activities 1908–1928 Derelict 1974– Currently available mapping Little change identified.
Geology Plasticity =0	Made ground was found in all exploratory holes across the site and was predominantly composed of clays and sands.
Thickness	From 0.00m to 14.3 m
Hydrogeology (Groundwater)	Groundwater level across the site is typically around 10.00–12.00m below ground level.
Hydrology	Surface water located to the east of the Site
Topography	The overall topography of the site gently slopes in a north/north–east direction.
Neighbouring use north	Industrial area with colliery and copper works 400m north of the site
Neighbouring use east	Industrial area with colliery works 400m east of he site
Neighbouring use south	No available information (Site offices)
Neighbouring use west	Industrial area with glass works 600m west of the site

Building and other structures	Comprises an existing administration building to the southwest, vehicular access/weighbridges and a site office to the south, a staff and visitor carpark covering the majority of the proposed development, and a storage area to the north.
Underground services	Not mention
Storage of materials and old tanks	no evidence of any former tanks
Radon	Not mention
Invasive species	Not mention
Future user	Steel framed main building housing the power plant, buildings and facilities related to everyday use of the facility.

Case study 2: Redevelop agriculture site to residential units with private gardens

The second case study run through the DSS was to undertake an initial appraisal of the geo–environmental conditions and to obtain data on chemical and geotechnical characteristics of the site for use by a developer and contractors who are considering a potential development opportunity. A report has been provided that is based on a brief desk study and fieldwork comprising soil sampling, ground gas monitoring and in–situ geotechnical testing. Selected soil samples were scheduled for a chemical analysis suite for common contaminants, and some samples were prepared for geotechnical testing. Monitoring was carried out on the site for water levels and hazardous ground gas. Further case study information is surmised in Table *7.3*.

Table 7.4 Preliminary site information for case study two

Case study 2	Preliminary information
Site history	The Site is indicated to have been agricultural from the earliest map edition to the current map edition.
Geology	The Site is underlain by topsoil comprising silty sandy clay across the Site from ground level to depths of between 0.20 and 0.30 m
Hydrogeology	Groundwater was recorded at depths of between 1.6 to 2.9 m
Hydrology	The Site and surrounding area are within an area with a large network of field drains and a 'Y' shaped drainage channel is present on–Site.
Topography	Flat
Neighbouring use north	Residential properties
Neighbouring use east	Agriculture
Neighbouring use south	Residential properties
Neighbouring use west	Residential properties
Flood	The Environment Agency considers the site and the immediate surrounding area to be at risk from flooding from rivers or seas without flood defences.
Radon	According to the site check data, the site is not in a radon affected area and no radon protection measures are required.
Proposed Development	500 residential units with private gardens

7.4.2.1 PRAofBS validation

Preliminary information for each case study was entered into the DSS Tool, the outputs were then compared with the results of reports. Table 7.5 presents the pollutant output of the PRAofBA compared to the report results. Table *7.5* does not show pollution levels as it was viewed that these are not important in this stage. However, it is evident that the outputs of the DSS Tool, in most cases, agree with the results of the reports.

There are some potential issues with the output. The first discrepancy relates to the possible contaminants listed. For instance, within case study one, contaminant Barium and PCBs are highlighted by the DSS Tool but these were not mentioned in the original reports. There are several explanations for this: firstly, these particular contaminants may not have been tested and, therefore, not reported or, secondly, the DSS Tool over expects the types of contaminants because it is based on the findings of previous historical site data. Similarly, the DSS Tool output for case study two suggested Asbestos may be present, which was also not mentioned in the original report. Whilst this suggested to be a potential issue, it is not a major difficulty for the DDS tool as it is better to edge on the side of caution and overpredict possible contaminants rather than to underpredict them. However, this could increase site investigation costs if it recommends testing the contaminants that may not be present.

The second issue with the DSS Tool outputs are the reverse situation. Whereby, contaminants identified in the original reports are not highlighted by the DSS Tool. For instance, in case study one, the DSS Tool failed to identify Selenium and Vanadium, while in case study two Mercury was not identified. Obviously, this is a potentially greater issue than the first situation. However, in defence of the DSS Tool, the geology in case study one is made ground, making the expectation of pollutants extremely difficult, as the made ground may contain a wide range of contaminants from various provenances. To resolve this issue, a recommendation section could be provided by the DSS Tool to suggest a new expected contaminant. However, this may be viewed as being not entirely useful for the end–user.

It is important to note that, unlike the DSS Tool, the original reports did not consider all potential hazards, such as radon, invasive species and underground services. Therefore, the DSS Tool may provide a worthwhile role in drawing an investigator’s attention to a particular hazard, which will help them avoid any future problems down the line (such as a planning authority rejecting an application because some hazards are missing).

Table 7.5 Contaminants outputs of the PRAofBA compared with report results

Contaminant	Case study 1	PRAofBS	Case study 2	PRAofBS
Acid	✓	✓	✓	✓
Aromatic hydrocarbons	✓	✓		
Arsenic	✓	✓	✓	✓
Asbestos		✓		✓
Benzene	✓	✓		
Barium		✓		
Cadmium	✓	✓	✓	✓
Chlorinated Aliphatic hydrocarbons	✓	✓		
Chromium	✓	✓	✓	✓
Copper	✓	✓	✓	✓
Free Cyanide	✓	✓		
Lead	✓	✓	✓	✓
Mercury	✓	✓	✓	
Nickel	✓	✓	✓	✓
Oil/fuel hydrocarbons	✓	✓	✓	✓
PAHs	✓	✓		
PCBs		✓		
Phenol	✓	✓		
Selenium	✓		✓	✓
Vanadium	✓			
Zinc	✓	✓	✓	✓

Comparing the results regarding possible pathways and targets proved to be less straightforward, where the information related to the interpretative/factual reports is not presented in the manner as the outputs generated by the tool. For example, the device shows potential hazards in terms of their likelihood of occurrence by ordered, percentages and represents this as pie charts. With a view to compare the results from the tool and the reports, Table *7.6* was compiled. This shows further results from the DSS Tool and relevant information from the original reports. Again, the DSS Tool seemed to perform well, identifying similar hazards.

Table 7.6 Pathway outputs of the tool compared with report results

Case study 1 Pathway	PRAofBS outputs
Risks to Groundwater by leaching and migration.	The presence of surface water increases contaminants' movement to adjacent sites and/or groundwater, which raises risks to human health and aggressive attack to building materials.

Migration of contaminants to groundwater. Risks to Surface Water Receptors from by surface water, leaching and migration.	The presence of groundwater increases contaminants' movement to adjacent sites and/or surface water systems, which raise risks to human health and aggressive attack to building materials.
Accumulation of ground gases. very low risk levels across the Site.	Emission of noxious or asphyxiating mine gases
Case study 2	**PRAofBS tool outputs**
Leaching and migration through any perched/shallow groundwater present beneath the Site	Presence of groundwater increase the movement of contaminants to adjacent sites and/or surface water systems. Which rise risks to human health and aggressive attack to building materials.
Direct contact and permeation	Contaminants in the ground can pose a risk to potable water supply by permeating plastic water.

Results from the DSS Tool and the report for case study one both highlight risks to groundwater and surface water by leaching and migration. The DSS Tool also suggests gas emissions. Otherwise, although the preliminary information of the original report indicates that the overall topography of the site is gently sloping in a north/northeast direction, it does not illustrate the potential impact of this slope on the movement of the contaminants. However, the tool stresses that the site topography of this case study could cause the migration of pollutants downslope and widen the spread of contaminants, especially if there was slope failure. In terms of case study two, the DSS Tool shows strong agreement. It highlights the migration of contaminants to groundwater, gas migration and contaminant permeation through water pipes.

It is clear from both case studies that the DSS Tool predicts well the pathway of contaminants, the concerns of the DSS Tool were the fact it did not identify the direction of contaminants. Further, the DSS Tool determines the risks for only one stratigraphic layer but this could be overcome by assessing each layer separately. The expectation of the receptor also proved to be effective. Table *7.7* details the output from the DSS Tool and related information from the original reports.

Table 7.7 Receptor outputs of the tool compared with report results

Case study 1	PRAofBS tool outputs
Human health Human health (site users). Exposure through: • Ingestion • Inhalation • Dermal routes	**Human health** Female child (0 to <6 years); Gardeners. Exposure though:

Building materials The ground is described as being 'aggressive'. Below ground pipework should be protected.	• Direct ingestion of soil • Ingestion of home–grown produce • Ingestion of soil attached to home–grown • Inhalation of indoor and outdoor dust • Inhalation of indoor and outdoor vapours • Dermal contact with soils and dust **Building materials** Contaminants in the ground can pose a risk to potable water supply by permeating plastic pipe water.
Case study 2	**PRAofBS tool outputs**
Human health Future site users (workers and visitors) • Direct contact • Ingestion of dust and vapours • Inhalation of dust and vapours **Building materials** Presence of chemicals potentially aggressive to concrete of buildings and structures.	**Human health** Female child (0 to <6 years); Gardeners. Exposure though: • Direct ingestion of soil • Ingestion of home–grown produce • Ingestion of soil attached to home–grown • Inhalation of indoor and outdoor dust • Inhalation of indoor and outdoor vapours • Dermal contact with soils and dust **Building materials** Contaminants contact with concrete cause damage leading to loss of strength, stiffness and cracking.

The DSS Tool results were in strong agreement with both case study reports, matching similar sensitive receptors. The DSS Tool provides more details about the human receptor with the appropriate pathway exposure. In addition, the DSS Tool details how the construction materials could be affected by the site chemical conditions. However, even though the results are encouraging, it is important to pay attention that the two case studies may be suggested to be straightforward examples and that more in–depth appraisal of the DSS Tool needs to be conducted by assessor using it daily.

7.5 Chapter Summary

This chapter reviewed the development of a Web–based Decision Support System (DSS) Tool for Preliminary Risk Assessment of Brownfield Sites (PRAofBS). The DSS Tool outputs are intended to be used as information to help assessors and other stakeholders to identify potential hazards associated with brownfield sites at an early stage.

The PRAofBS DSS was developed based on the data collected, analysed and validated from the conceptual framework (Chapter 6). The validation of the DSS Tool in this chapter adopted two approaches. Firstly, a quantitative approach carried out through a structured online survey. The findings of this process have shown strong support for the PRAofBS DSS Tool in terms of its ease of use and the quality and level of information, which is highlighted by four out of every five participants suggesting they would recommend the DSS Tool to colleagues. Secondly, information from two case studies were run through the DSS Tool to compare the outputs. These suggest strong agreement between findings for both. Therefore, it is inferred that the PRAofBS DSS Tool is useful in assisting assessors and other stakeholders to identify potential brownfield sites hazards at the preliminary stage of their investigations.

8. CHAPTER 8: CONCLUSIONS, CONTRIBUTIONS TO KNOWLEDGE AND FUTURE RESEARCH

8.1 Introduction

This chapter presents and synthesises the conclusion of the research work. Accordingly, the research objectives are restated and discussed with the summary of findings in respect of each objective and major conclusions highlighted. The novelty of this research and the contributions to new knowledge concerning the risk assessment of brownfield sites are also detailed. Finally, the chapter also considers limitations of this research, before providing recommendations and offering directions for future research.

8.2 Review of the Thesis Objectives

This section restates and reviews each of the objectives that were listed in the opening chapter.

Objective 1: To critically review brownfield site definitions, their scope within the UK legislation context and their assessment process.

A comprehensive review of brownfield site literature (Chapter two) revealed they can be a major environmental engineering problem, particularly in countries with industrial a legacy (ies) because they can harm human health, ecology system, property and infrastructure. Thorough interrogation of brownfield sites typically requires multi–disciplinary expertise, multi–stage approaches and multi–agency regulation. Large volumes of information are needed to make a full risk assessment of the site. The risk assessment process is complex and is typically undertaken using a phased approach, which fits within a tiered assessment structure in line with the framework set out in CLR 11. Three tiers are adopted for risk assessment, normally involving: (i) preliminary risk assessment (PRA), where information collection may include a desk–top study, site reconnaissance and exploratory site investigation to develop an initial conceptual site model; (ii) generic quantitative risk assessment (GQRA), where samples are collected and any contaminant concentrations are compared with generic assessment criteria (GAC) appropriate to the generic land use based on generic assumptions about soil properties, pathways and receptors; and (iii) detailed quantitative risk assessment (DQRA) is considered to generate site–specific assessment criteria. It may include further targeted information collection to support the generation of the requirements and typically involves the use of modelling software to estimate the movement of contaminants in the media, such as air and plants, and the detailed exposure features of the receptor.

Objective 2: To conduct a critical review of the literature to identify potential hazards associated with brownfield site development.

A comprehensive literature review of the potential hazards associated with brownfield sites was conducted (Chapter 3). The review revealed that development on brownfield sites presents considerable hazards considering the difficulties in developing because of their constraints, which can include physical characteristics and contamination issues. This has increased significantly in many parts of the country where most new housing developments occur on land where the previous usage has left a wide range of physical, chemical and/or biological hazards. The source of hazards in brownfield sites is based on three main types, firstly contaminated sites that have left a legacy of contamination from operational activities. Secondly, sites with poor engineering quality (landfill sites) share the chemical and biological hazards with contaminated sites. Meanwhile, they arise from the inability of the site to support the buildings, caused by the poor bearing capacity of the site. Thirdly, existing buildings in brownfield sites, including industrial and commercial buildings, arise hazards related to the release of chemical hazards during demolition activities.

Objective 3: Examine the state–of–the–art of existing risk assessment models and tools of brownfield sites.

A systematic literature review was conducted on risk assessment tools for contaminated sites (Chapter 3). These tools have been identified from searching through leading academic databases and other professional sources. For each of the identified devices, the relevant risk assessment stages, harm type, hazard category, receptor type and pathways are reported. From these analyses and the underlying subject of the review, a critical discussion was conducted to identify the knowledge gaps and propose recommendations to bridge these gaps for each aspect. Findings reveal that despite growing interest in the development of risk assessment tools, there are persistent knowledge gaps identified by this study, which serve as a basis for future research direction to where more advanced practical tools could be invented. For instance, it is evidenced that there is a shortfall in practical tools available to contaminated site assessors conducting investigations at the preliminary risk assessment stage. Addressing this opening can benefit the planning process, coordinated between relevant stakeholders and reduce uncertainty in the decision–making of contaminated site developers.

Researchers can make use of this review to define their future directions and efforts in developing better tools. Conversely, based on the existing list of tools reviewed, users can now select the most appropriate instrument to suit their objectives, needs, and contexts.

Objective 4: Develop and validate the conceptual framework to guide the design of the DSS.

This was achieved through a two–stepped process, which is explained beneath.

Step 1: Conceptual framework development

The framework development started from a conception derived from the literature review that there is a strong need for a framework that will enable investigators in conducting a preliminary risk assessment. However, the development of the conceptual framework went through two stages: (i) stage one involved identifying the essential information for preliminary risk assessment of brownfields sites, and (ii) stage two involved identifying the potential hazards associated with each information type.

For stage one, a systematic review was conducted to identify the key information to establish the pollutant linkage model. This review was conducted on academic databases and grey literature. The academic database includes Scopus, American Society of Civil Engineers (ASCE) and other leading search facilities. While, grey literature includes government reports, technical reports etc. The research keywords were a combination of "Preliminary" "Hazard assessment", "Hazard identification", "Contaminated sites", "Brownfield sites", "Site investigation", "Site appraisal" and "Site report". They were selected for their comprehensive coverage on the subjects of preliminary assessment of brownfield sites and combined cover the majority of the main journal and conference publications.

As a result of this process, the following information was identified to establish pollutant linkage model:

- Source:
    - Site history
    - Surrounding areas
    - Building and other structures

  - Underground services
  - Storage of materials and old tanks
  - Previous mining activities
  - Presence of radon
  - Invasive species
  - Made ground
- Pathway
  - Site geology
  - Site hydrology
  - Site hydrogeology
  - Site topography
- Receptor

For stage two, a comprehensive literature review concerning the identification of potential hazards associated with brownfield sites was conducted. Eventually, 65 potential hazards were extracted from the extant literature. These potential hazards were assessed and weighted, based on an online questionnaire survey with brownfield site professionals.

Step 2: Conceptual framework validation

Validation of the conceptual framework has accomplished the main objective of the study. A quantitative data collection was conducted via an online survey, and the subsequent statistics and VAHP analysis were used to gauge the requirements to establish pollutant linkage model and weighting the potential hazards associated with each information respectively.

Various deductions have been drawn from the quantitative analysis, which have importance on the preliminary assessment of brownfield sites. Firstly, statistical analyses indicate the identified information is important in identifying pollutant linkages; whereby, site history, made ground, invasive species, previous mining activities, storage of materials, presence of radon, underground services, building and other structures are the most frequent used information to identify the potential source of hazards in brownfield sites. Meanwhile, site geology, site hydrology, site hydrogeology and site topography were rated as top information to identify the pathway movement of the contaminants. While future site use scenario information is critical to identify the critical receptor of the population most likely to be exposed and/or susceptible to the presence of soil contamination. Secondly, some professional roles have different views to hazards. For instance, geophysicist, geochemists and hydrologist do not raise concerns regarding ground movement resulting from the removal of storage and tanks, while this hazard was rated important by the other roles.

Objective 5: Design and test a web–based DSS, based on the outcome of the framework validation.

An online web decision support system was developed based on the framework validation findings and implemented via the accessible link http://PRAofBS.herokuapp (Chapter 7). Its purpose is to increase its accessibility as well as enhancing its uptake in the UK and beyond. Both quantitative and qualitative data analyses were conducted to validate the web–based DSS Tool. The quantitative data collection was conducted via an online survey, then statistical analysis has been conducted to validate the usefulness of the DSS in helping investigators and other stakeholders to identify potential hazards associated with brownfield sites at the initial stage of risk assessment process. Moreover, the statistical analysis was carried out also to confirm that the DSS Tool has been built robustly and appropriated for acceptance by its end users, as is the intention of the research. The results of this process have shown the success of the PRAofBS DSS in terms of its ease of use and the quality and level of information. Approximately 80% of participants mentioned they would recommend the tool to colleagues.

To 'road–test' the DSS, a qualitative data analysis via a real–life case studies have been used to demonstrate its worth. Two case studies containing information and data relating to preliminary risk assessment were utilised, and the outputs from the DSS Tool were compared with expert judgments. The results show that the PRAofBS DSS Tool was perceived to be useful in assisting assessors and other stakeholders in identifying hazards in brownfield sites at the preliminary stage. The DSS predicted potential contaminants with a reasonable match with those observed, despite the limited input data for the case studies. Furthermore, the identification of hazards related to source, pathway and receptors were in general agreement with case study reports.

Objective 6: Provide conclusions, contribution to new knowledge, and future recommendations.

The achievement of this objective is addressed by this chapter as given in the following sections. The final objective of the research is discussed in this chapter under Section 8.5.

8.3 Contributions to New Knowledge

The contributions this study provides to new knowledge are:

1. **Identification of the knowledge gaps in the current approaches particularly regarding preliminary risk assessment**

   This research systematically reviewed the sites of available risk assessment tools that could be suitable for brownfield sites. From a set of 222 articles, 31 tools for review were identified. The analysis was conducted with respect to the following aspects: risk assessment stages, type of harm, hazard category, receptor type and pathways. From these analyses There are several knowledge gaps identified in this study, which serve as a basis for future research direction to where more advanced practical tools could be developed or refined. For instance, there is evidence suggesting a shortfall in useful tools available to contaminated site assessors conducting investigations at the preliminary risk assessment stage. Addressing this issue can benefit the planning process, coordinated between relevant stakeholders, and reduce uncertainty in contaminated site developers' decision–making. In addition, more comprehensive tools are needed to reduce uncertainties regarding the interpretation of toxicological information and reference values, in particular, for stakeholders with limited knowledge for toxicological data. Current approaches to risk assessment are limited for contaminated sites, as these do not cover the hazards which arise from biological contamination and poor land quality. Furthermore, the majority of tools address risks to human health and groundwater, while buildings are not considered. Finally, the pathways that are considered are also insufficient. Researchers can make use of this review to define their future directions and efforts in developing better tools. Conversely, based on the existing list of tools reviewed, users can now select the most appropriate one to suit their objectives, needs, and contexts.

2. **Examination the level of professional agreement and disagreement in key information for preliminary risk assessment of brownfield sites.**

   This study aimed to determine the criteria necessary for the initial risk assessment of brownfield site based on the pollutant linkage model (Source-Pathway-Receptor) with focus on the level of agreement and disagreement between expert groups in their perception of the criteria requirements. A total of thirteen criteria were identified through a systematic review and presented to expert groups to gauge their level of importance in relation to preliminary assessment of brownfield sites. Participants were required to identify the appropriate criteria to identify the pollutant linkage components.

   The results of statistical analyses of seventy-six expert responses indicate that the top i criteria to identify the source of hazards are history of the site, made ground, invasive species, previous mining, storage of materials and old tanks, presence of radon, underground services and buildings and other structures. Furthermore, site geology, site hydrology, site hydrogeology and site topography were rated as the top criteria to identify the pathway movement of the contaminants. While future site use scenario criteria is critical to identify the critical receptor of the population most likely to be exposed and/or susceptible to the presence of soil contamination.

   The study renders the preliminary risk assessment exercise to be not only more holistic and integrated but also to reduce uncertainty in risk assessment by ensuring that all eventualities along with their respective significance have been encapsulated at the initial stage of risk assessment. Another important element of the study brought out is that the same hazard and associated risk can be of varying significance to different professionals. So much so that a crucial hazard in the eyes of one practitioner may not be a hazard at all in the eyes of another practitioner, merely due to the difference in their backgrounds. This variation in views and interests of different professionals can help the risk assessor to develop the pollutant linkage model of the brownfield site more categorically and systemically, encapsulating all possible hazards, pathways and receptors. A diversity of professional engagements would enhance the capability of the risk assessor to signify and appropriately prioritise hazards in the preliminary risk assessment with greater confidence.

Finally, this study advocates the need for more inclusive criteria to come from the perspective of various professional practitioners in view of their different backgrounds; thereby, enabling more holistic and complete identification of hazards (with their diverse implications) for a given brownfield site.

3. Development of an innovative framework for preliminary risk assessment of brownfield sites

This study has proposed a comprehensive and easy–to–use innovative framework for preliminary risk assessment of brownfield sites. The components of the framework were identified through a critical review of the literature. These components are: (i) pollutant linkage model, (ii) site characteristics and (iii) potential hazards. The study revealed 65 known potential hazards associated with brownfield sites, which have been prioritised and classified by experts, before interrogation by VAHP. These priorities established amongst the potential hazards can help developers, planners and other stakeholders when assessing and developing brownfield sites. In such situations, the priorities can be used to identify and inform the direction of the next stages of any future risk assessment.

The contributions of this study are two–fold: Firstly, it renders the preliminary risk assessment exercise to be not only more holistic and integrated but also reduces uncertainty in the risk assessment process by ensuring all eventualities, along with their respective significance, have been identified at the initial stage of a risk assessment, which may represent a strong starting point to successfully conduct more detailed risk assessment and remediation. Secondly, potential hazards resulting from this study can enhance effective environmental communication between stakeholders, which should speed–up the planning process and be an assistive tool to regenerate and redevelop brownfield sites more efficiently and effectively; while, preserving the natural environment for which there are escalating pressures from the government, policies, people and even the global sustainability agenda.

4. **Development of a web–based Decision Support System.**

The outcomes of this study offer practical benefits. Firstly, experts have validated and judged the DSS to be a useful tool in identifying potential hazards associated with brownfield sites. Secondly, the tool could contribute to industry in terms of supporting investigators and different stakeholders in the preliminary risk assessment of brownfield sites in an easy, understandable and user–friendly way.

8.4 Limitation of the Research

Despite this study achieving its intended aim and objectives, and like many other doctoral studies, the research has some limitations that should be readily acknowledged. These include:

- Notwithstanding the DSS validated and assessed positively, feedback suggests opportunities may exist to further perfect the function/design of the tool. Beside the fact that some of them have been fixed, other comments (outside the boundaries of the research) will be considered in future work.
- Further improvements to the tool are needed for its adoption to wholly useful on complex brownfield sites. For example, the DSS identifies only hazards associated with one layer of site geology, while sites may include different layers. In addition, some sites have a history with different types of industrial use, but the current DSS provides only hazards for one previous industrial use.
- Adopting an online survey approach also has disadvantages since it was challenging to gain a high response rate and gather a representative sample. Therefore, it is unknown how the results might vary if a higher number of professionals had participated in this research.
- Whilst this study identified 65 potential hazards associated with brownfield sites, this number could be expanded to include hazards related for plants, animals, air etc.

8.5 Recommendations and Possible Future Research

Two types of recommendations are proposed, those which can augment the built environment, particularly, the architecture, engineering and construction (AEC) sector, and those which can steer the direction(s) of any future research studies.

- Future research may focus more on simple tools using numerical solutions of contaminant fate transport models, in particular at a preliminary risk assessment stage. Otherwise, tools based on exposure models, databases, and dose–response models should be comprehensive and user–friendly, enabling professionals with limited knowledge to look deeper into data and make decisions based on this.
- Buildings (the built environment) are not considered as receptors. Therefore, there is a need for tools which more explicitly, also consider building materials as receptors, where hazards (such as aggressive chemicals, combustible materials, expansive slag) of a contaminated site can pose a risk to building materials. A more specific example could be an acid (such as sulphuric acid coming from batteries) that can adversely affect concrete foundation in the form of corrosion.
- Extending the DSS Tool to include mitigation actions for each potential hazard. For example, based on the list of predicted contaminants, the DSS Tool could provide advice regarding health and safety requirements for site workers. In addition, the DSS Tool could also be extended to include a remediation option for potential hazards.
- Further research could also to take advantage of the growing development of Building Information Modelling (BIM) by developing an innovative system that integrates design decision tasks throughout brownfield site redevelopment with BIM processes. The system will assist designers to reflect on the safety implications of their design decisions. The fundamental concern of the system is the identification, evaluation, and mitigation of potential hazard at the design stage of brownfield site development. The proposed system will add a new functionality to popular BIM tools (such as Autodesk REVIT).

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APPENDIX I: Conceptual Framework Validation Survey

Research title: Web-Based Decision Support System for Preliminary Risk Assessment of Brownfield Sites

I am a PhD student at the University of the West of England UWE in the department of Architecture and Built Environment. My research project seeks to develop a Decision Support System tool that will assist assessors to conduct prelimininary risk assessment in order to identify potential hazards associated with brownfield sites.

The survey has four parts:

PART 1: General informaation about the participant
PART 2: Validating the necessary information to identify hazards associated with brownfield sites
PART 3: Ranking the potential hazards associated with brownfield sites
PART 4: Comments & Suggestions

I am seeking the help from those who have experience in brownfield site development in completing the survey below which should take 15-20 minutes .

Please notice:

The university requests to provide the below documents to inform you about the study, to explain the benefits and any risks of participation, the attached documents are :

Information_sheet_.docx

Consent_Form.docx

Privacy_Notice_for_participants.docx

If you have any further questions about this survey or the research please do not hesitate to contact me via email address at mahammedi.charfeldine@uwe.ac.uk.
By clicking on the agreement to participate at the start of the online survey you are indicating your informed consent. Before clicking please ensure that you agree with all of the points below:

1. I have read and understood the information in the Participant Information Sheet which I have been given to read before and is clear;

2. I have been given the opportunity to ask questions about the study;

3. If appropriate I have had my questions answered satisfactorily by the research team;

4. I agree that anonymised quotes may be used in the final report of this study;

5. I understand that my participation in this research study is completely voluntary and that I am free to withdraw at any time, without giving a reason;
I agree to take part in the research.

Yes

No

→

UWE Bristol | University of the West of England

Part 1: General information

Q1. How would you best describe your professional role or job title?

Q2. How many years of experience do you have in this profession?

- Less than three years
- 3-5 years
- More than 5 years

Q3. How many years of experience do you have in the management of brownfield sites?

- Less than three years
- 3-5 years
- More than 5 years

← →

UWE Bristol | University of the West of England

PART 2: Validate the necessary information to identify hazards associated with brownfield sites

Q4. Please rate whatever the following information is important to identify the sources of hazards-Obstruction (e.g. tanks, old foundations, services)

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
History of the site					
Surrounding areas					
Building and other structures					
Underground services					
Storage of materials and old tanks					
Previous mining activities					
Presence of radon					
Invasive species					
Made ground					

Q5. Please rate whatever the following information is important to identify the sources of hazards-Ground movement (e.g. settlement)

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
History of the site					
Surrounding areas					
Building and other structures					
Underground services					
Storage of materials and old tanks					
Previous mining activities					
Presence of radon					
Invasive species					
Made ground					

Q6. Please rate whatever the following information is important to identify the sources of hazards-Contaminated sites (e.g. chemical contaminants)

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
History of the site	○	○	○	○	○
Surrounding areas	○	○	○	○	○
Building and other structures	○	○	○	○	○
Underground services	○	○	○	○	○
Storage of materials and old tanks	○	○	○	○	○
Previous mining activities	○	○	○	○	○
Presence of radon	○	○	○	○	○
Invasive species	○	○	○	○	○
Made ground	○	○	○	○	○

Q7. Please rate whatever the following information is important to identify the sources of hazards-Contaminated sites (e.g. biological contaminants)

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
History of the site	○	○	○	○	○
Surrounding areas	○	○	○	○	○
Building and other structures	○	○	○	○	○
Underground services	○	○	○	○	○
Storage of materials and old tanks	○	○	○	○	○
Previous mining activities	○	○	○	○	○
Presence of radon	○	○	○	○	○
Invasive species	○	○	○	○	○
Made ground	○	○	○	○	○

Q8. Please rate whatever the following information is important to identify the sources of hazards-Biodegradation of fills

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
History of the site	○	○	○	○	○
Surrounding areas	○	○	○	○	○
Building and other structures	○	○	○	○	○
Underground services	○	○	○	○	○
Storage of materials and old tanks	○	○	○	○	○
Previous mining activities	○	○	○	○	○
Presence of radon	○	○	○	○	○
Invasive species	○	○	○	○	○
Made ground	○	○	○	○	○

Q9. Please rate whatever the following information is important to identify the sources of hazards-Invasive species

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
History of the site	○	○	○	○	○
Surrounding areas	○	○	○	○	○
Building and other structures	○	○	○	○	○
Underground services	○	○	○	○	○
Storage of materials and old tanks	○	○	○	○	○
Previous mining activities	○	○	○	○	○
Presence of radon	○	○	○	○	○
Invasive species	○	○	○	○	○
Made ground	○	○	○	○	○

Q10. Please rate whatever the following information is important to identify contaminant movement

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
Site geolog (i.e., soil permeability and soil thickness)	○	○	○	○	○
Site hydrogeolgy (i.e., presence of groundwater)	○	○	○	○	○
Site hydrology (i.e., presence of surface water and flood zones)	○	○	○	○	○
Site topography (i.e., flat site and steep site)	○	○	○	○	○

Q11. Please rate whatever the following information is important to identify human health as receptor of hazards in brownfield sites.

	Not at all important	Slightly important	Moderately important	Very important	Extremely important
Future land use scenario (e.g. residential, commercial)	O	O	O	O	O

Q12. Please rate whatever the following information is important to identify buildings as receptor of hazards in brownfield sites.

	Not all important	Slightly important	Moderately important	Very important	Extremely important
Building materials	O	O	O	O	O

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Q13. If there is any information missing on this survey, please list it below

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PART 3: Rank the potential hazards associated with brownfield sites development

Q14. Please rank (from the most to the least likely) the following **hazards** associated the information of **surrounding areas (residential)** to your site in terms of their likelihood of occurrence

1. Pollutants migration from brownfield sites to neighbour residential (.e.g. in the period of heavy rainfall or snowmelt)
2. Excavation of brownfield site may disturb contaminates and releasing them into water course and water supplies which may pose risk to neighbour residential

Q15. Please rank (from the most to the least likely) the following **hazards** associated the information of **surrounding areas (industrial)** to your site in terms of their likelihood of occurrence

1. Pollutants migration from industrial/commercial site to adjacent sites (e.g. in the period of heavy rainfall or snowmelt.)
2. Excavation of the industrial/commercial site may disturb contaminates and releasing them into water course and water supplies which may pose risk to neighbour residential.

Q16. Please rank (from the most to the least likely) the following **hazards** associated with the information of **presence of buildings and other structures** in brownfield sites in terms of their likelihood of occurrence

1. Hazards related to demolition activities of existing buildings and other structures.
2. Old foundations failure due to chemical soil attack that lead to foundations degradation
3. Hazards from sharp objects (e.g. glass, metallic objects)

Q17. Please rank (from the most to the least likely) the following **hazards** associated with the information of **underground services (water pipes and sewers)** in brownfield sites in terms of their likelihood of occurrence

1. Damage to water pipes and sewers may cause floods
2. Contaminants in the ground can pose a risk to potable water supply by permeating plastic water
3. Leaks of water from underground pipes can affect adjacent services and reduce support for other structures
4. Damage to a sewer pose risks to the health of workers from exposure to raw sewage.

Q18. Please rank (from the most to the least likely) the following **hazards** associated with the information **underground services (gap pipes)** in brownfield sites in terms of their likelihood of occurrence

1. Risk of fire and explosion due to flammable gases.
2. Risk of leakage due to damage of connections.
3. Risk of asphyxiation due to inert gases such as nitrogen and argon.
4. Risk of fire and explosion due to flammable gases.
5. Risk of release contents due to elevated pressure.

Q19. Please rank (from the most to the least likely) the following **hazards** associated with the information **underground services (electricity cables)** in brownfield sites in terms of their likelihood of occurrence

1. Explosive, fire or flames that may result when a live cable is penetrated by a sharp object.
2. Damage of electricity cables may pose risk to nearly services
3. Hazards of electrical cables to burn hands, face and body
4. Cables which have been damaged but left unreported and unrepaired, or which have deteriorated with age.

Q20. Please rank (from the most to the least likely) the following **hazards** associated with the information **of storage of materials and old tanks** in brownfield sites in terms of their likelihood of occurrence

1. Chemicals and other liquid raw materials stored in tanks and silos
2. Ground instability related to removing tanks and underground storages

Q21. Please rank (from the most to the least likely) the following **hazards** associated with the information of **previous mining activities** in brownfield sites in terms of their likelihood of occurrence

1. Pollution incidents resulting from mine water and contaminated shaft fill
2. Subsidence and collapsing of voids due to the presence of large voids at shallow depth.
3. Emission of noxious or asphyxiating mine gases
4. Spontaneous combustion of coal by exposure to atmospheric conditions

Q22. Please rank (from the most to the least likely) the following **hazards** associated with the information **of invasive plants** : brownfield sites in terms of their likelihood of occurrence

1. Aggressive plant may cause damage to the structure of a building such as drains, services, and walls.
2. Invasive plants may cause immense landslides and soil erosion
3. Health issues due to contact (e.g. dermal contact, swallowing) with invasive plants

Q23. Please rank (from the most to the least likely) the following **hazards** associated the information of **made ground** in brownfield sites in terms of their likelihood of occurrence

1. Failure of construction materials, because of their vulnerability to aggressive ground conditions
2. Hazards for buildings and occupants, arising from combustion
3. The migration of contaminants from landfill site over time increase the possibility of groundwater to be contaminated.
4. Damage to buildings due to volume changes in fill caused by physical, chemical or biological reactions
5. The generation of methane and carbon dioxide with volatile organic compounds (VOC) as result to microbial activity

Q24. Please rank (from the most to the least likely) the following potential **hazards** associated with the information of **site topography (flat site)** in brownfield sites in terms of their likelihood of occurrence

1. Horizontal sites increase infiltration and vertical movement of accumulated contaminants towards groundwater.
2. Horizontal sites reduce contaminants flow which creates a source of contamination that increase environment pollution

Q25. Please rank (from the most to the least likely) the following potential **hazards** associated with the information of site topography (steep site) in brownfield sites in terms of their likelihood of occurrence

1. Spreading of contaminants as result of slope failures
2. Migration of contaminants in the direction of the slope

Q26. If there is any hazard missing on this survey, please list it below

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Part 4: Comments & Suggestions

Q27. Please feel free to provide any comments or suggestions below

Finally, thank you for your participation in this survey. If you need further information, please feel free to contact me at Mahammedi.charfeldine@uwe.ac.uk.

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APPENDIX II: PRAoBS DSS Tool Validation Survey

UWE Bristol University of the West of England

Research title: Web-Based Decision Support System (DSS) for Preliminary Risk Assessment of Bownfield Sites.

I am a PhD student at the University of the West of England UWE, the department of Architecture and Built Environment. This survey aims to collect data for validating the PRAoBS (Preliminary Risk Assessment of Brownfield Sites) tool, to assist assessors to identify potential hazards associated with brownfield sites at preliminary risk assessment stage. The PRAoBS tool is designed based on the data collected through a survey of 76 participants.
I am seeking the help from those who have experience in brownfield site management in completing the survey below which should take 15 minutes. Please use the link below to access the Tool:
http://PRAOBS.herokuapp.com

Please notice:
The university requests to provide the below documents to inform you about the study, to explain the benefits and any risks of participation, the attached documents are :
Information_sheet_.docx

Consent_Form.docx

Privacy_Notice_for_participants.docx
If you have any further questions about this survey or the research please do not hesitate to contact me via email address at mahammedi.charfeldine@uwe.ac.uk.
By clicking on the agreement to participate at the start of the online survey you are indicating your informed consent. Before clicking please ensure that you agree with all of the points below:

1. I have read and understood the information in the Participant Information Sheet which I have been given to read before and is clear;

2. I have been given the opportunity to ask questions about the study;

3. If appropriate I have had my questions answered satisfactorily by the research team;

4. I agree that anonymised quotes may be used in the final report of this study;

5. I understand that my participation in this research study is completely voluntary and that I am free to withdraw at any time, without giving a reason;
I agree to take part in the research.

Yes

No

→

APPENDIX II

Q1. How would you best describe your professional role or job title?

Q2. How many years of experience do you have in this profession?

Less than three years

3-5 years

More than 5 years

Q3. How many years of experience do you have in the management of brownfield sites?

Less than three years

3-5 years

More than 5 years

← →

Q4. How is your first impression of the Tool in terms of graphical user interface?

Excellent	Good	Average	Poor	Terrible
1	2	3	4	5

Q5. How clear is the tool? (easy to understand)

Extremely unclear	Somewhat unclear	Neither clear nor unclear	Somewhat clear	Extremely clear
1	2	3	4	5

Q6. Do you find the entire process of using the Tool easy?

Extremely difficult	Somewhat difficult	Neither easy nor difficult	Somewhat easy	Extremely easy
1	2	3	4	5

Q7. How would you rate the quality of information presented?

Not at all useful	Slightly useful	Moderately useful	Very useful	Extremely useful
1	2	3	4	5

Q8. To what extent does the tool provide you with the appropriate level of information to identify potential hazards at preliminary assessment stage?

Excellent	Good	Average	Poor	Terrible
1	2	3	4	5

Q9. Would you recommend the tool?

Yes

No

Q10. In order to improve the tool, please provide any additional comments?

Finally, thank you for your participation in this survey. If you need further information, please feel free to contact me at Mahammedi.charfeldine@uwe.ac.uk.

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