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ABSTRACT

Purpose – Reusing brownfield sites often raises concerns about the health and safety of both workers involved in site remediation and redevelopment and subsequent site users. A preliminary risk assessment is essential to determine if a brownfield site is contaminated and to ensure that any redevelopment activities are safe and appropriate for the intended use. Despite increased interest in advancing risk assessment tools, there is limited availability of instruments for brownfield site assessors to consult during preliminary risk assessments. This study addresses this gap by designing and validating a web-based decision support system (DSS) designed to assist investigators and various stakeholders in identifying potential hazards associated with brownfield sites during the preliminary investigative stage.

Design/methodology/approach – The development of the Preliminary Risk Assessment for Brownfield Sites (PRABS) tool involved a rigorous verification and validation process. Initially, the tool's functionality was tested by applying it to two real-world contaminated site scenarios and comparing the results with those from previous preliminary risk assessments. Following this, fifty brownfield experts were invited to evaluate the usability and effectiveness of the developed tool.

Findings – The functionality tests demonstrated that the PRABS tool produced results consistent with previous site reports, showing no significant discrepancies or anomalies. During validation, the majority of participants found the tool easy to use and recognised its potential value. They particularly appreciated the level and quality of information provided by the output of the tool, highlighting its usefulness in preliminary risk assessments.

Research limitations/implications – This study focuses on the initial stages of risk assessment for brownfield sites and suggests that the PRABS tool offers a valuable new approach for assessors and stakeholders. However, further investment and subsequent research are needed to refine the tool and explore its full potential as a commercial product.

Practical implications – Governments, environmental agencies, and private developers can significantly benefit from the PRABS tool by enhancing the efficiency and accuracy of preliminary risk assessments for brownfield sites. Through facilitating safe and appropriate redevelopment activities, this tool promotes the effective and secure reuse of contaminated lands.

Originality/value – This study introduces a novel web-based DSS for preliminary risk assessment of brownfield sites, addressing a critical gap in available assessment tools. The PRABS tool not only provides a practical solution for current needs but also sets the stage for future advancements in environmental risk management, contributing significantly to the field.

Keywords: Brownfield Sites, Contaminated sites, Site investigation, Preliminary risk assessment, Decision Support System (DSS).

1. Introduction

Brownfield land refers to land previously used or developed, which may be contaminated, making it challenging to reuse or redevelop (Koutra *et al.,* 2023). These areas are typically found in urban or industrialised regions and may include former factories, petrol stations, or even disused landfills (Fernandes *et al.,* 2020). Such properties often remain unused due to the expense and complexity of environmental cleanup, rendering them unappealing to developers. These sites often present environmental and health hazards due to the presence of harmful substances or contaminants. Nevertheless, brownfield sites also offer significant potential for redevelopment and economic expansion (Loures and Vaz, 2018). In 2022, England identified over 23,000 brownfield sites, spanning more than 27,000 hectares, publicly recognised as suitable for reuse. These sites include vacant and derelict land with the potential to accommodate 1.2 million homes (Campaign to Protect Rural England, 2022). Nevertheless, since brownfield sites have been utilised in the past, they may contain hazards that present potential risks, especially to a range of receptors including humans, ecosystems, water quality, property, plants, animals, etc (Mahammedi at al., 2022a). For instance, Brofiscin Quarry was a former limestone quarry used as a landfill for industrial waste (Robin, 2014). The site contained a mix of hazardous chemicals, and the risk assessment did not account for the potential for the contaminants to migrate and impact nearby water sources. The inadequacies in the risk assessment led to difficulties in developing effective remediation strategies (Shahra and Wu, 2023). Elsewhere, there have been observations of elevated cadmium concentrations surpassing acceptable limits in livestock organs, attributed to the presence of lead and cadmium from a former mining site in Morocco (Nouri and Haddioui, 2016). Similarly, in China, leaf and root vegetables, in particular, have been contaminated by cadmium from a zinc smelter (Li *et al.,* 2016). All the incidents mentioned above serve as a clear reminder of the potential risks associated with the reuse of brownfield sites. The redevelopment of brownfield sites frequently presents significant market risks, introducing challenges related to the perception associated with the reclamation of contaminated land and its subsequent impact on market values (Mahammedi et al., 2020a). A comprehensive study conducted by (Bartke, 2011) highlights the lasting effects of these redevelopment efforts. Even with comprehensive decontamination measures are implemented, the average market value of these areas sees a significant decline of 12.25%. Moreover, the study results highlight a troubling pattern environmental pollution exacerbates the negative impact that commercial properties have on the value of nearby residential homes. This suggests that the consequences of urban redevelopment extend beyond the immediate vicinity, impacting the broader residential real estate landscape (Beames *et al.,* 2018). The documented challenges emphasise the need for nuanced strategies in mitigating the economic consequences associated with brownfield revitalisation, not only addressing contamination concerns but also safeguarding property values and fostering sustainable urban development (Bunce, 2017). Navigating the challenges of brownfield redevelopment requires a crucial understanding of the complex dynamics between environmental remediation, property markets, and community perceptions. This comprehension is essential for achieving both economic viability and positive societal impact (Koutra *et al.,* 2023).

Land quality risk management (LQRM) refers to identify and assess if there is an unacceptable risk. Also, assess what remediation options are suitable to manage the risk (Environment Agency, 2023). Preliminary Risk Assessment (PRA) is the starting point of LQRM. It is predominantly a desk-based information collection process, often involving site reconnaissance, also referred to as a Desk Study (Hellawell and Hughes, 2021).

Its primary objective is to determine whether there are potentially unacceptable risks on the site, ascertain if further information is required, or decide if the site should be subject to ongoing review (Environment Agency, 2016). Through an analysis of a diverse range and substantial volume of information, the preliminary risk assessment aims to identify potential or existing constraints that could impact the site. This proactive approach aims to mitigate issues later in the project, where addressing such problems becomes increasingly costly (Martin and Toll, 2006). Challenges associated with brownfield site redevelopment leaves a significant research gap that needs to be filled. The challenges associated with brownfield sites are primarily related to their environmental condition, economic viability, and community impact (Kovalick Jr and Montgomery, 2017). For example, the environmental difficulties associated with brownfield sites arise from their past use, which frequently entailed the release of hazardous substances like chemicals, heavy metals, and petroleum products (Kovacs and Szemmelveisz, 2017; Pellegrini *et al.*, 2021). Without proper management, these contaminants can pose risks to both human health and the environment. Addressing these concerns involves comprehensive assessment, clean up, and monitoring efforts during the remediation of brownfield sites to guarantee the effective containment or removal of any existing contamination (Espana *et al.*, 2018). Another challenge in the assessment of brownfield sites is commonly required expertise and knowledge from several disciplines, including geotechnics, geology, hydrology, hydrogeology, chemical, geo-environment etc, 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 (Mahammedi et al., 2022a). This may increase misunderstanding and communication issues between different stakeholders.

1.1 Problem Statement

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 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 (Mahammedi et al., 2020). The intricacies inherent in brownfield site assessments are expected to persist unless the creation of comprehensive and easy tools enables assessors to streamline complexity, thereby bolstering their confidence in decision-making (Mahammedi et al., 2020b). 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 (Gebremariam et al., 2019). 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 (Swenson, 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 Aim and Objectives

The aim of this study is to design and validate a decision support system (DSS), named Preliminary Risk Assessment of Brownfield Sites (PRABS), 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, where the examples of diverse stakeholders would include, for instance, risk assessors, local planning authorities, regulator, developers, civil engineers, architectures, landowners, investors, and alike. Moreover, the DSS will enable them to promote safer redevelopment and minimise the risks to future occupants of brownfield sites and neighbouring lands, on the top of the tool being communal platform of an effective communication between them as it is for both experts and non-experts.

Given the costly and time-consuming nature of preliminary risk assessments of brownfield sites, it is neither economical nor feasible to thoroughly examine numerous sites. Hence, it is crucial to pinpoint potential hazards and likely contaminants before initiating the exploratory phase of the investigation. The development of the prototype system aims to address several concerns:

1) Provide guidance to staff at various levels of involvement in the investigation, spanning from junior engineers to senior consultants. Consider this more as a supportive tool for professionals rather than a substitute for expertise.
2) By inputting and gathering data, establish a systematic approach to the preliminary risk assessment.
3) Employing various abiotic and biotic indicators, such as tolerant plant species and soil staining, to aid in identifying potential contaminants on the site and associated hazards, such as buried tanks.
4) Refer to information from published literature, such as geological maps, to support the initial risk assessment of brownfield sites.

2. Methodology

This study is a follow-on from past sister studies (Mahammedi *et al.*, 2020a; Mahammedi *et al.*, 2022a) in which knowledge gaps were identified with systematic review and conceptual framework was produced and validated, respectively. In this study the framework is furthered to develop DSS for PRABS in the sense that can be used as a tool by the industry for preliminary assessment of brownfield sites. This tool is also validated by experts in the industry as well as by being applied on real-word case studies. All these stages are described schematically in Figure 1.

Figure 1 The main stages adopted in the development process of the Decision Support System (PRABS) (Source: figure created by authors)

The methodology for achieving the aim of this study encompasses two key stages: Stage 4 focuses developing the Decision Support System (DSS) tool, while Stage 5 emphasises the validation of this tool In Stage 4, a combination of PostgreSQL database management, HTML5, and Cascading Style Sheets (CSS) is integrated to craft a user-friendly and efficient web-based application. The database is central to the system, storing and organising data on potential hazards to human health and buildings. HTML5 is employed for structuring webpage content, while CSS is utilised for designing the user interface and enhancing functionality.

Moving to Stage 5, the validation of the DSS tool was executed employing a dual approach encompassing both quantitative and qualitative methodologies. This ensures a comprehensive assessment of its functionality and user satisfaction. Firstly, an online survey was designed and deployed to determine users' perspectives and requirements. The survey, consisting of seven sections, commenced with generic inquiries to profile the participants. Subsequent sections delved into specific aspects: the graphical user interface (GUI) evaluation, ease of use assessment, quality and quantity of information provided by the DSS, its utility in aiding stakeholders' decision-making regarding brownfield site development and solicited constructive feedback for future enhancements. To ensure the effectiveness of the online survey, a panel of industry professionals was targeted using a purposive sampling technique. This method facilitated the selection of participants with relevant expertise, aligning with the objective of capturing diverse insights crucial for tool development (Al-Mhdawi et al., 2024)The questionnaire was piloted by three academic professionals to enhance clarity and relevance, ensuring that it was user-friendly and meaningful for respondents (Al-Mhdawi et al., 2023a; Al-Mhdawi et al., 2023b). Secondly, functional testing was conducted by evaluating tool inputs and outputs against two real-life case studies. This rigorous examination validated the accuracy and reliability of data outputs.

3. Description of PRABS

The DSS workflow, illustrated in Figure 2, provides a systematic approach to conducting preliminary risk assessments for brownfield sites. It is based on the Source Pathway Receptor (SPR) model outlined in Part 2A of the Environment Protection Act 1990. This model highlights the connections between potential hazards, migration pathways, and receptors within contaminated sites, forming the basis for a comprehensive risk assessment strategy. Through a fourteen-step process, it reveals valuable insights into the nature of site risks. The initial steps (1 to 9) focus on understanding the sites history and physical attributes, including land use, surrounding infrastructure and any underground structures or storage materials present. These steps provide a foundational understanding of potential contamination sources, essential for subsequent risk evaluation. Moving forward, steps 10 to 12 shift focus towards mapping out migration pathways through detailed analysis of site geology, hydrogeology, and topography. By consulting technical literature and expert knowledge, the workflow identifies key factors influencing the movement of contaminants within the site, thus enabling a more accurate assessment of potential exposure pathways. Subsequently, step 13 directs attention to identifying receptors, particularly vulnerable receptors, or sensitive environments at risk of exposure to soil contaminants. Through careful consideration of future land use scenarios and user demographics, this step ensures that risk assessments are tailored to address the specific needs and concerns of the site's stakeholders. Finally, step 14 evaluates the impact of site conditions on building materials, recognising the potential long-term consequences of contamination on infrastructure integrity. By integrating these diverse elements into a cohesive framework, the DSS workflow provides a robust foundation for informed decision-making and regulatory compliance, helping to safeguard both public health and environmental quality in brownfield redevelopment projects.

Figure 2 The workflow diagram of PRABS (Source: figure created by authors)

To demonstrate how the sets of rules predict hazards and contaminants, several examples are presented below:

Example 1: History of the site

IF	*"History of the site"* is Mining
THEN	*"The Chemical hazards- The key chemical contaminants"* are Metals and their compounds, Arsenic, Zinc, Barium, Cadmium, Copper, Fer, Chromium, Lead, Nickel, Mercury
AND	*"Organic and inorganic"* are Chlorinated Solvents, Phenol, Aromatic hydrocarbons, PCbs, PAHs, Oil/fuel hydrocarbons, Dioxins and furans, Asbestos, Acid, Cyanide
AND	Expansion Fills: the presence of slags from iron and steel-making processes will possibly expand the soil after decades after deposition, causing damage to structures and roads.
AND	Shallow mine working: the possibility of the presence of large voids at shallow depth will increase issues caused by collapsing voids.

Example 2: Underground services

IF	*"Underground services"* is YES
THEN	*"Obstruction hazards: The possibility of contaminants migration to other sites through underground pipes"*
AND	*"Obstruction hazards: 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"*

Example 3: Structure and existing building

IF	*"Structure and existing building exist"* is YES
THEN	*"Obstruction hazards: Structures and buildings exist in previously used land rise concerns about demolition activities. For example, asbestos can be found in any industrial structures or residential building built or refurbished before the year 2000"*
THEN	*"Obstruction hazards: Although the possibility to reuse the existing foundation, but there are inherent risks including foundation failure under loads and differential settlement. Excessive deformation such as punching shear or one-way shear failure of part or all foundations could lead to collapse of the structure"*

4. Demonstration of PRABS

In general terms, a web-based system comprises three primary components: Frontend, Backend, and Database (MacIntyre *et al.,* 2011). The Frontend, often termed the 'client-side,' is the part of a website directly accessed by users. It encompasses the visual and interactive elements users directly engage with, including text, images, buttons, navigation menus, and other user interface components. Meanwhile, the Backend manages the logic and functionality behind the scenes, handling tasks such as processing user requests and managing data interactions. The Database, a crucial component, stores and organises the system's data, facilitating efficient data management and interaction with the Backend. Together, these components work harmoniously to deliver a functional and user-friendly web-based experience (Krosing and Mlodgenski, 2013). HTML, Javascript and CSS are the languages used for front end development. Secondly, the Backend comprises a site's structure, system, data, and logic. 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) (Godbolt, 2016). Thirdly, 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.

PRABS tool 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 3 shows the relationship between the tables in the database.

Figure 3 The relationship between tables in a DSS database (Source: figure created by authors)

The preliminary risk assessment, utilising the PRABS tool, is performed on the homepage screen. Users are required to select the appropriate information on the given homepage. To generate the outputs, users must click on the 'Generate Report' button. The features of the data entry page/home page are explained in Figure 4 below.

Figure 4 The home page of PRABS (Source: figure created by authors)

The outcomes of the PRABS tool are illustrated in Figure 5, which shows the information selected by the users. The chart pie in the output page shows the rank of the potential hazards.

Figure 5 Output of the preliminary risk assessment of PRABS (Source: figure created by authors)

5. Validation of PRABS

Figure 6 presents an overview of the DSS validation process, employing two distinct methodologies. Firstly, a qualitative approach was executed via an online survey, engaging experts to assess aspects such as the graphical user interface (GUI), information depth, and data quality. Secondly, a qualitative analysis was conducted by evaluating the tool's outputs against real-life case studies, ensuring alignment and reliability of the information provided.

Figure 6 The validation process of PRABS (Source: figure created by authors)

5.1 Quantitative Validation of the PRABS Tool

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

5.1.1 The Reliability of Questionnaire Data

The reliability of the data collected in this second survey was determined by the Cronbach's alpha test, which shows is a strong internal consistency amongst the data (i.e. > 0.70) (Table 1).

Table 1. The reliability of the survey data tested using Cronbach's Alpha (Source: table created by authors)

Reliability Statistics	
Cronbach's Alpha	No. of Items
0.76	5

5.1.2 Demographics of the Participants

Participants were required to have some level of experience in brownfield site management. Participants' experiences distribution 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. 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.

5.1.3 Validation Criteria

5.1.3.1 The graphical user interface (GUI)

According to (Gao *et al.,* 2019), 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 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". 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 2. T–tests were conducted to measure the significance of the means, 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 2, that the p–value is <0.05 (n=52), which means any differences between the groups (participants with experience <3 years and participants with experience >5 years) are significant. This could be because 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 2) is considered applaudable, 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.

5.1.3.2 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. Participant responses to the ease/difficultly using the tool shows most participants reported that the DSS was easy to use (~80% saying it is extremely easy or somewhat easy). Table 2 shows that the overall mean of participants was 4.17 (SD=0.981; n=52), which is considerably high. 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, because 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. 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 2.

5.1.3.3 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 results 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”. 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 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.

5.1.3.4 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. Many of the participants (88.4%) indicated their support for the level of information presented in the too. 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 2. T–test was conducted to measure the significance of the means. Table 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.

5.1.3.5 Recommending the developed 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 *et al.,* 2017). 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 2. Summary of the survey results on the validation of the DSS Tool *(Source: table created by authors)*

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.

5.1.3.6 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.

5.2 Qualitative Validation of the PRABS 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 (described below), which included data related to preliminary site investigation, contamination test results and interpretative statements.

5.2.1 Case study 1: 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 3.

Table 3. Preliminary site information for case study one (Source: table created by authors)

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.

5.2.2 Case study 2: Redeveloping an 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 4.

Table 4. Preliminary site information for case study 2 (Source: table created by authors)

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

5.2.3 Discussion

Preliminary information for each case study was entered into the DSS Tool, the outputs were then compared with the results of reports. Table 5 presents the pollutant output of the PRABS compared to the report results. This 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 PRABS tool, but these were not mentioned in the original reports. There are several explanations for this: firstly, these 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 PRABS tool output for case study one suggested Barium 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 PRABS tool outputs are the reverse situation. Whereby, contaminants identified in the original reports are not highlighted by the PRABS 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 PRABS tool, the original reports did not consider all potential hazards, such as radon, invasive species and underground services. Therefore, the PRABS 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 5. Contaminants outputs of the PRABS compared with report results (Source: table created by authors)

Contaminant	Case study 1	PRABS	Case study 2	PRABS
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 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 6. Pathway outputs of the tool compared with report results (Source: table created by authors)

Case study 1 Pathway	PRABS 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	**PRABS 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 PRABS 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 PRABS 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 details the output from the PRABS tool and related information from the original reports.

Table 7. Receptor outputs of the tool compared with report results (Source: table created by authors)

Case study 1	PRABS tool outputs
Human health Human health (site users). Exposure through: • Ingestion • Inhalation • Dermal routes **Building materials** The ground is described as being 'aggressive'. Below ground pipework should be protected.	**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 in the ground can pose a risk to potable water supply by permeating plastic pipe water.
Case study 2	**PRABS 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 PRABS tool results were in strong agreement with both case study reports, matching similar sensitive receptors. The PRABS tool provides more details about the human receptor with the appropriate pathway exposure. In addition, the PRABS 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 PRABS tool needs to be conducted by assessor using it daily.

6. Theoretical and practical Implications

The PRABS tool is grounded in theoretical principles of risk management, environmental science, and urban planning. It draws on academic research, regulatory frameworks, and established methodologies for hazard identification and risk assessment. The theoretical underpinning ensures that the DSS aligns with best practices in the field and provides a sound and comprehensive approach to addressing the challenges associated with brownfield site redevelopment. The practical application of the PRABS offers stakeholders a multifaceted approach to brownfield site management. Firstly, it aids in the systematic identification of potential hazards associated with these sites, encompassing environmental, health, and safety considerations. This information empowers stakeholders to make well-informed decisions through comprehensive risk assessments, fostering safer and more sustainable redevelopment strategies. The PRABS plays a pivotal role in promoting safer redevelopment practices, minimising risks for both future site occupants and neighbouring lands. Furthermore, it serves as a communal platform that enhances communication among diverse stakeholders, facilitating the exchange of data, insights, and concerns for a collaborative decision-making process. By optimising resource allocation through a focus on high-priority risks and implementing targeted mitigation measures, the PRABS improves the overall efficiency of the risk assessment process, contributing to the responsible and effective redevelopment of brownfield sites.

7. Conclusion and future research

This study has proposed and implemented a comprehensive and easy–to–use decision support system for preliminary risk assessment of brownfield sites. The validation of the PRABS tool in this study 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 PRABS tool in terms of its ease of use and the quality and level of information, which is highlighted by approximately 80% of participants suggesting they would recommend the PRABS tool to colleagues. Secondly, 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 PRABS tool was perceived to be useful in assisting assessors and other stakeholders in identifying hazards in brownfield sites at the preliminary stage. The PRABS tool 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. The contributions of this study offer practical benefits. Firstly, it enables the initial risk assessment process to be more comprehensive and integrated and reduces complexity in the risk assessment process by ensuring that all probabilities, along with their significance, are identified at the initial stage of the risk assessment. This could be a strong starting point for successfully conducting a more detailed risk assessment and remediation. secondly, the developed PRABS can promote effective environmental communication among stakeholders, which should speed up the planning process and help develop brownfield sites more efficiently and effectively, while preserving the natural environment. Based on this study, it is proposed that future work could extend the PRABS 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. Despite its contributions, this study has several limitations. First, the DSS identifies only hazards associated with one layer of site geology, even though sites may include multiple layers, which limits the comprehensiveness of the hazard identification process. Second, adopting an online survey approach posed challenges in achieving a high response rate and gathering a representative sample, making it uncertain how the results might vary with a higher number of professional participants. This limitation affects the generalisability of the findings. Finally, while this study identified 65 potential hazards associated with brownfield sites, this number could be expanded to include hazards related to plants, animals, and air, indicating the need for a more inclusive approach to hazard identification. Given these limitations, future research should focus on addressing these gaps. One way to enhance the DSS is by developing simple tools using numerical solutions of contaminant fate transport models, especially at the preliminary risk assessment stage. Such tools would provide a more detailed analysis of site conditions. Additionally, tools based on exposure models, databases, and dose-response models should be comprehensive and user-friendly, enabling professionals with limited knowledge to analyse data and make informed decisions. This would make the DSS more accessible and effective for a broader range of users. Moreover, extending the DSS Tool to include mitigation actions for each potential hazard is also recommended. For example, based on the list of predicted contaminants, the DSS Tool could offer advice on health and safety requirements for site workers, ensuring their protection while working on contaminated sites. Additionally, the DSS Tool could provide remediation options for potential hazards, offering practical solutions for managing and reducing risks.

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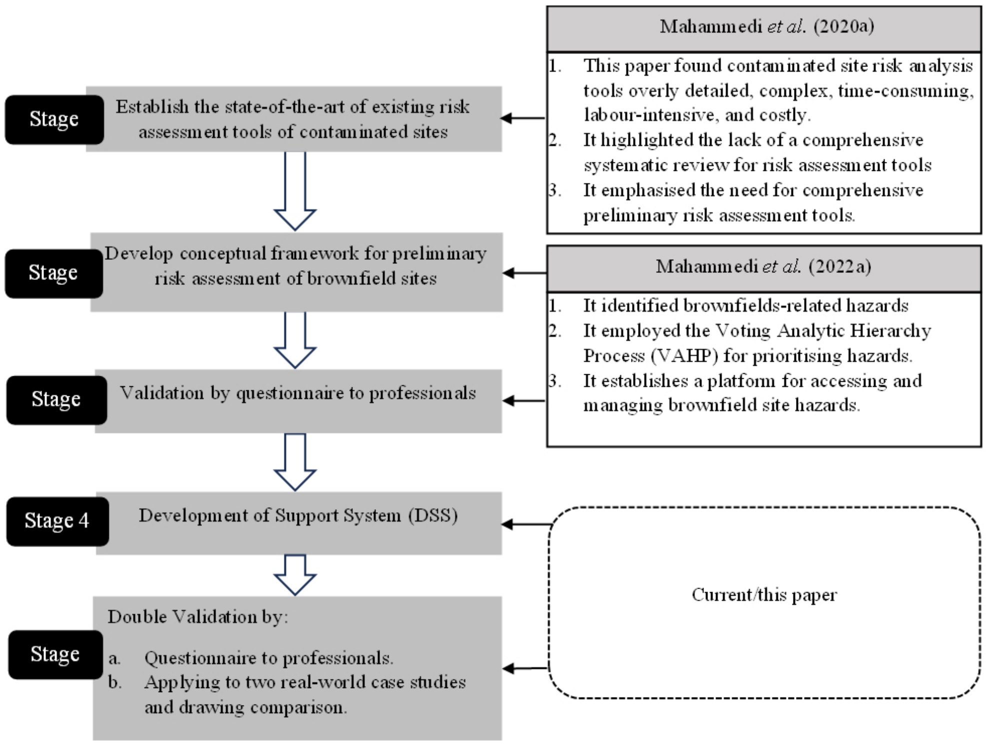

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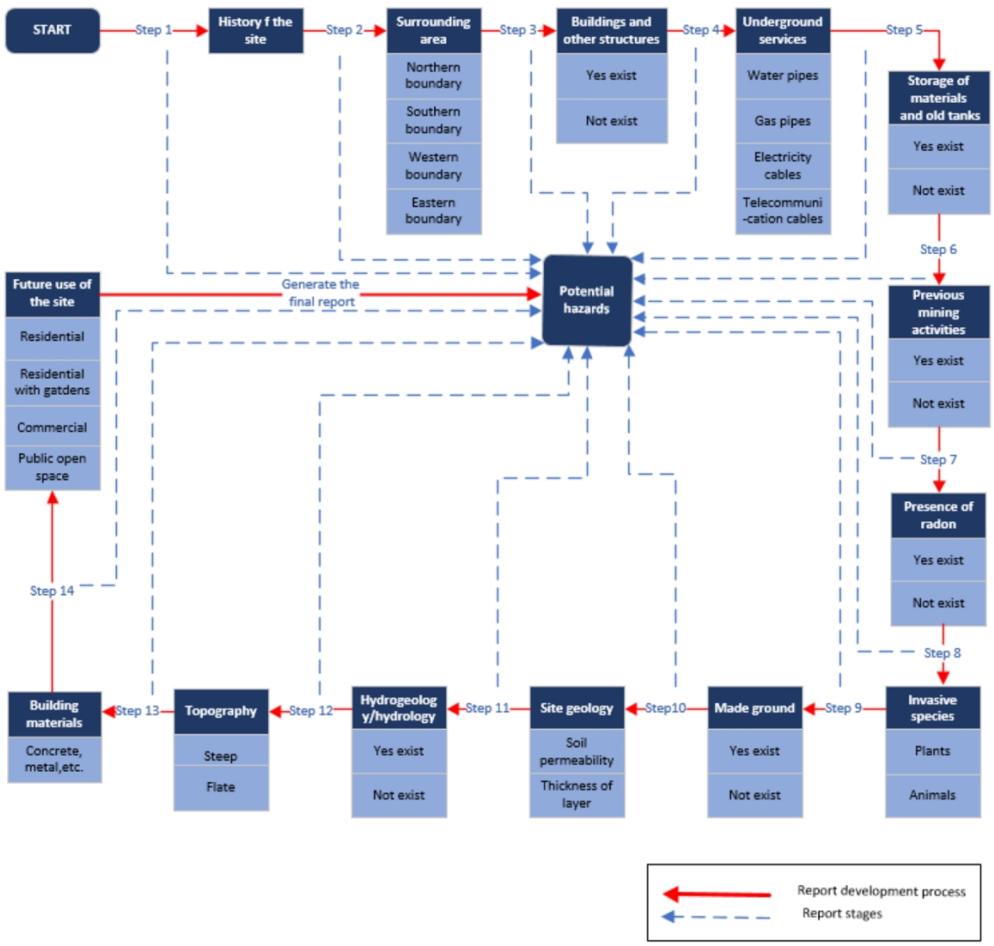

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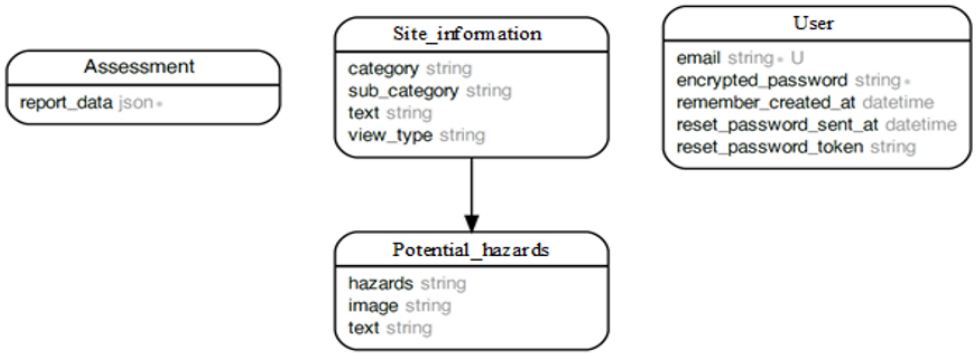

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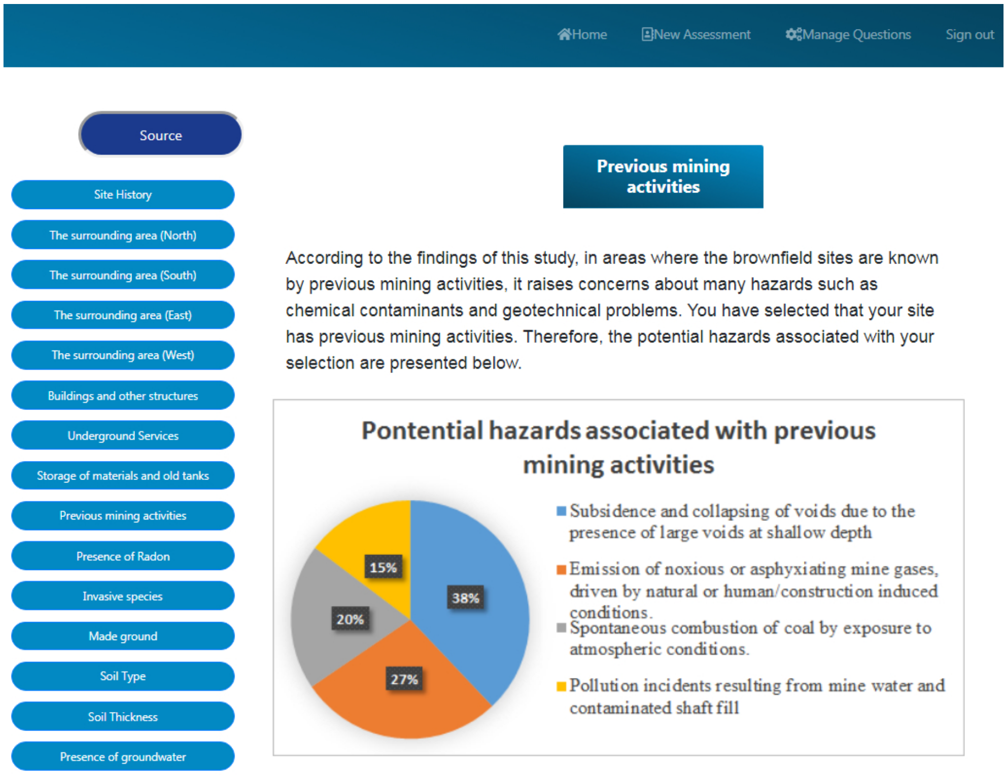

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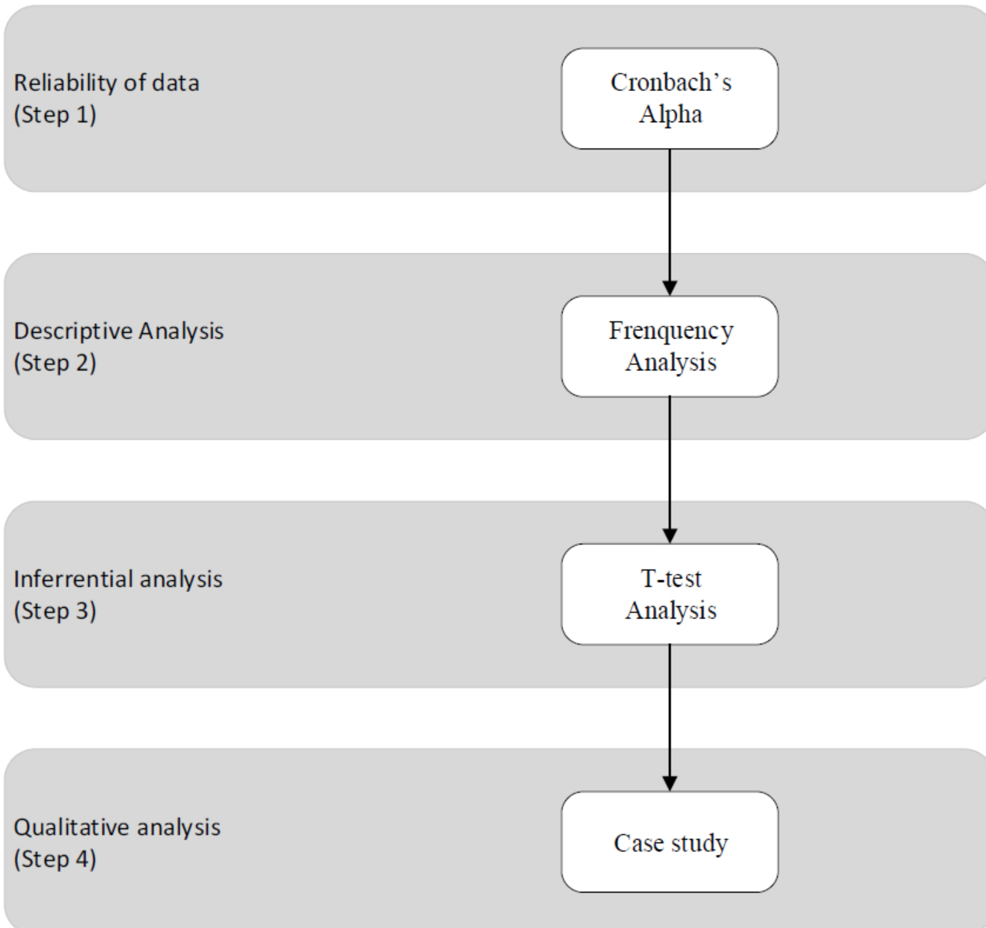

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