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Review

A critical review of decision support systems for brownfield redevelopment

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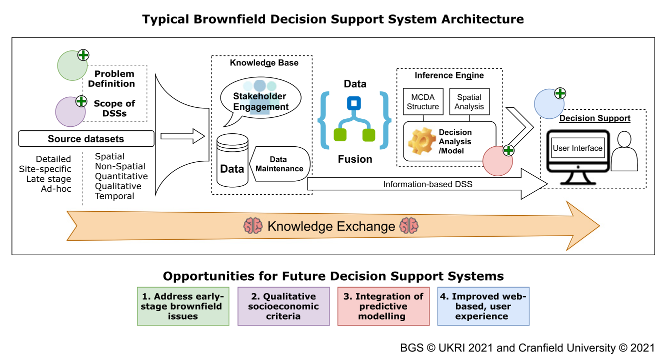
HIGHLIGHTS

- Brownfield DSSs reviewed focused on environmental and contamination issues.
- Opportunity for holistic DSSs in early stages of brownfield redevelopment
- Opportunity for predictive modelling to form part of brownfield DSSs
- Opportunity for improved visual graphical user interfaces
- Opportunity for powerful web-based functionalities to be adopted in brownfield DSSs

GRAPHICAL ABSTRACT



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ABSTRACT

Over the past two decades, many decision support systems (DSSs) have been developed to support decision makers and facilitate the planning and redevelopment process of brownfields. Existing systems are however often siloed in their approach and do not fully capture the complexity of brownfield sites from a sustainable development point of view. This critical review provides an insight into the development and implementation of DSSs, published and emerging, together with assessment of their strengths, limitations and opportunities for future integration. Brownfields DSS applications include: remediation technology selection; and land use planning; and risk assessment. The results of this review lead the authors to identify four opportunities to improve brownfield DSSs: (i) increased use of qualitative socioeconomic criteria, particularly costs and economic variables, (ii) decision-support during the early stages of brownfield redevelopment, (iii) the integration of predictive modelling methods, and (iv) improvements of user interfaces and modern web-based functionalities.
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1. Introduction

Brownfield land is defined by the Concerted Action on Brownfields and Economic Regeneration NETwork (CABERNET) as sites that “have been affected by the former uses of the site and the surrounding land; are derelict or underused; have real or perceived contamination problems; are mainly in developed urban areas; require intervention to bring them back to beneficial use” (CABERNET, 2006).

It was estimated in 2014 that there are about 4.2 million brownfield sites within the European Union, of which around 340,000 are expected to be contaminated and in need of remediation prior to redevelopment (Van Liedekerke et al., 2014). Similarly in the USA, it is estimated that there are more than 450,000 brownfield sites that may be suitable for development (Green, 2018). Likewise, In England, similar potential for brownfield redevelopment is recognised, with an estimated 21,000 brownfield sites, with the potential to provide 1.06 million homes (CPRE, 2020). In Europe, brownfield sites are generally smaller (<1 ha) and are situated within urban communities (Pérez and Peláez Sánchez, 2017); whereas in the USA and China, brownfield sites tend to be larger and more complex sites (so-called ‘megasites’) located in remote locations or at the margins of cities (Coulon et al., 2016; Liu et al., 2014; Song et al., 2018). These variations in the scale and complexity mean that challenges and needs for developing brownfields can be quite different, and a country-specific tailored approach is needed to address environmental, economic and social issues (Brombal et al., 2015; Fraser et al., 2018). There is a worldwide network of sustainable remediation for a which help guide this aspect from brownfield redevelopment (CL:AIRE, 2021). The Sustainable Remediation Forum for the UK (SuRF-UK) defines sustainable remediation as “the practice of demonstrating, in terms of environmental, economic and social indicators, that the benefit of undertaking remediation is greater than its impact, and that the optimum remediation solution is selected through the use of a balanced decision making process” (Bardos et al., 2018). The planning and development process for brownfield sites can depend on project or site-specific requirements. Fig. 1 shows a typical planning and land development process for brownfield sites, highlighting the relationships between land use planning scale, development stage, uncertainty in decision making, and data needs.

Decision Support Systems (DSSs) are designed to enhance the value of data, information and understanding used to inform the brownfield development processes by planners, developers, contractors and their advisors. DSSs are classified into two main groups: (1) information-based, which present information and may include some data analysis (e.g. a map of interpolated concentrations of soil contamination (Ault and MacKenzie, 2006)), and (2) model-based, which typically incorporate a problem-solving element such as numerical decision analysis (Black and Stockton, 2009) (e.g. multi-criteria decision analysis (MCDA) for assessing landfill waste categorisation (Feo and De Gisi, 2014)). The range of decision-making methods currently available and being used within environmental management DSSs is summarised in Fig. 2. This review focuses solely on model-based MCDA DSSs, used to calculate, rank and sort optimum outcomes to support brownfield redevelopment. DSS method selection is dependent on the nature of the problem and the types of data and information that are being evaluated. Consequently this means that methods are tailored to address different tasks.

One of the most commonly employed DSS methods is MCDA. This method typically involves a subject expert assigning scores/weightings to datasets that describe different aspects of the problem being examined. By using an MCDA method several criteria associated with predefined options are assessed by experts, using weightings that relate to trade-offs across these criteria in order to produce scores or rankings of decision options (Velasquez and Hester, 2013). A simple but commonly used approach is for a user of MCDA to calculate the total value score for decision options as a linear weighted sum of its scores across several criteria. Analytical Hierarchy Process (AHP) (Saaty, 1984) is also common and is often used to establish criteria weightings by conducting a pairwise comparison between criteria (Huang et al., 2011; Saaty, 1984). These pairwise weightings are then checked using an AHP Consistency Index and adjusted if needed (Saaty, 1984). Fuzzy logic (Zadeh, 1965) is used less commonly and is a mathematical approach that allows multiple values to be processed through the same variable where a truth-value exists in so-called *fuzzy-space* between 0 (FALSE) and 1 (TRUE). Fuzzy systems provide a framework to enable examination of problems with uncertainty and non-linearity which allows for high flexibility and effectiveness in comparison to other methods as it is possible to combine several rules simultaneously (Di Nardo et al., 2019).

While there has been a great deal of research and development of DSSs over the last two decades, their uptake and use has remained slow within many developed nations, including the UK. This is because these tools are often isolated in their scope, meaning they do not fully capture complex situations such as those encountered for brownfield redevelopment, or they are not able to be fully integrated within existing decision-making structures (Ameller et al., 2020).

Despite slow growth, there has been a general upward trend in DSSs designed for the brownfield sector and their use in decision-making between 1998 and 2021, which is evaluated for this review. The status of DSSs for brownfield redevelopment applications is summarised, highlighting the advantages and limitations of existing systems along with opportunities for improvement and integration of future DSSs to support brownfield redevelopment. There is presently a renewed interest by land use planners and policy makers in developing brownfield land in preference to undeveloped (greenfield) land. When this coupled with digital transformation components of the 4th industrial revolution (Industry 4.0), this leads the authors to assert that brownfield DSSs are going to follow a resurgent trend.

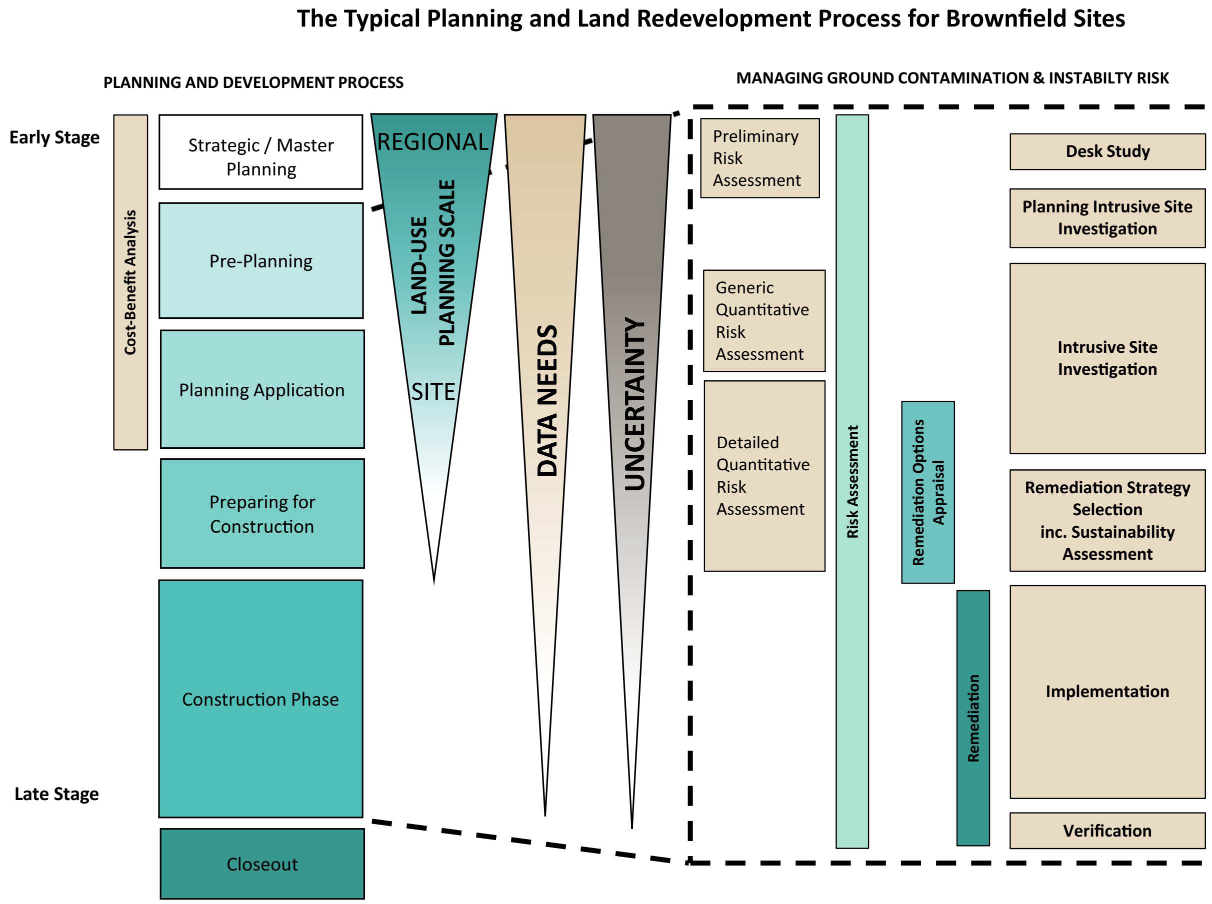

Fig. 1. The typical planning and land development process for brownfield sites indicating the relationship between steps within each domain showing how scale, data and uncertainty reduce over time. BGS © UKRI 2021 and Cranfield University © 2021.

2. Decision support systems for brownfield redevelopment

Scopus™ was used to search available literature using the following keywords: "Decision Support Tool*" OR "Decision Support System*" AND "Brownfield*" OR "Contaminated Land" (last accessed: 11th February 2021). The results of the search included 111 publications (peer-reviewed articles = 80, conference papers = 15, book chapter = 6, review = 5, short survey = 2, conference review = 2, books = 1). These results were filtered by relevant subject areas including Environmental Science, Decision Science, Social Science, Engineering, Earth and Planetary Science, Environmental Engineering, Mathematical Models, Management Science, and Operation Research and Management Sciences. Abstracts for each publication were screened manually to discount unrelated papers with similar phrasings, the filtering stage resulted in 54 publications that were each reviewed in detail.

The research reviewed shows a Eurocentric geographic trend (Supporting Information). Thirty-Seven of the fifty-four pieces of research reviewed were produced by European researchers, predominantly from Italy (n = 14), Germany (n = 7), and the UK (n = 6). These researchers also use European brownfields and stakeholder engagement to inform the design of their research and as case studies to demonstrate their DSSs. Aside from this, brownfield DSSs research has also been produced by researchers based in China (n = 8), the USA (n = 4), Australia (n = 2), Sweden (n = 2), Belgium (n = 2), and Finland (n = 2) among others.

Three main applications for brownfield DSS research were deduced from the literature: (i) the selection of remediation methods for soil and groundwater contamination (n = 15), (ii) evaluation of the land use suitability, including sustainability assessment (n = 15), and (iii) ranking/indexing of sites for land use suitability (n = 8). Other applications include, ecological risk assessment, facilitating stakeholder engagement with project development, and reviews. A tabulated summary of all 54 publications is provided in the Supporting Information.

2.1. Remediation method selection

A summary and scope of the DSSs applied to remediation method selection is provided in Table 1. These DSSs are all designed to help end-users select the most appropriate remediation method for soil and groundwater contamination. Eleven of the DSSs focus on the environmental and contamination constraints on remediation method selection after site investigation and characterisation is completed. Seven of the fifteen studies utilise a single MCDA methodology, with AHP proving the most popular.

Pizzol et al. (2009), Critto and Agostini (2009) and Carlon et al. (2008) used the remediation of the Porto Maghera site (~530 ha) in Italy to demonstrate the functionality of the "DEcision Support sYstem for the Requalification of Contaminated Sites" (DESYRE). DESYRE comprises six integrated GIS modules, using an AHP structure to rank specific remediation options (e.g. soil washing, landfill cap, electrokinetic separation). The modules use risk scores generated from combining contamination exposure and risk assessment models that incorporate detailed late-stage site investigation data (e.g. chemical concentration and distribution) as well as a small number of socioeconomic variables (e.g. site attractiveness for development).

Stezar et al. (2013) used a case study in Romania to compare and contrast DESYRE (Pizzol et al., 2009) with Spatial Analysis and Decision

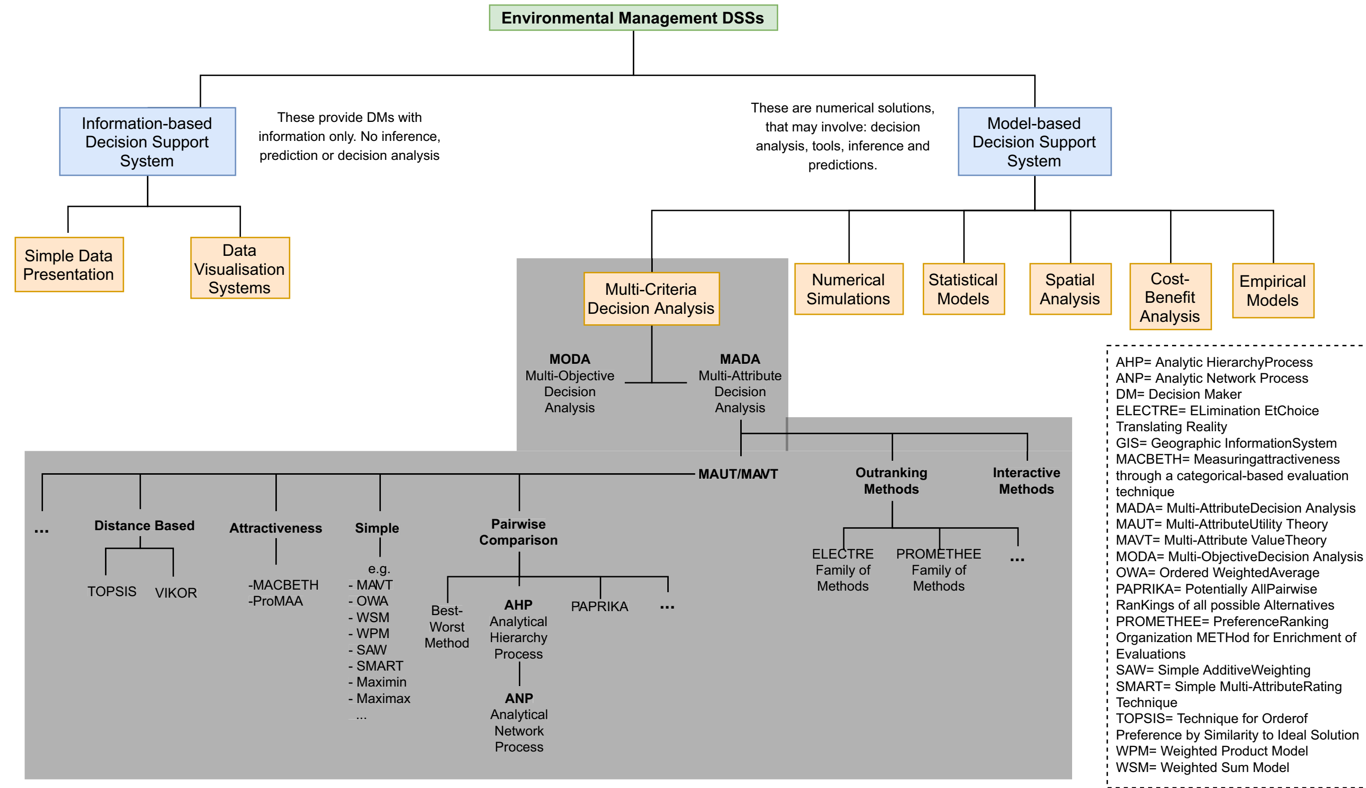

Fig. 2. Overview of decision-making methods used in Environmental Management DSSs. BGS © UKRI 2021 and Cranfield University © 2021.

Assistance (SADA) (Purucker et al., 2009), an ecological risk assessment tool. SADA contains modules that consider site characterisation, risk assessment (including human health), sampling location selection, with the ultimate aim of selecting a remediation method. The tools were compared based upon DSS evaluation criteria set out by Bardos et al. (2003) including: (1) defining the nature and extent of contamination, (2) remediation selection and optimisation, (3) human and ecological risk assessment, and (4) benefits analysis, including costs and/or risk reduction resulting from remediation. Stezar et al. (2013) conclude that SADA provides greater detail than DESYRE when quantifying residual risk to human health, aiding sampling planning, but SADA produces more meaningful outputs for stakeholders. Using SADA and DESYRE concurrently was seen as beneficial for enhancing decision making for the selection of a remediation technology based on greater data input, thereby allowing a more accurate model of contamination dispersal and highlighting risk areas (Stezar et al., 2013). Consequently, Stezar et al. (2013) suggest that in order to strengthen decision making, multiple DSSs should be used together.

Other studies have examined outliers of criteria weights in user decision logic that influence the selection of remediation methods. Examples include Li et al. (2018) who used a modified AHP for detecting outliers by including: (1) an expert competence classification, and (2) the Grubbs criterion (Grubbs, 1969), a statistical test, used to detect outliers in normally distributed data. They detected a large deviation in AHP rankings caused by different expert's preferences in their analyses, thereby indicating the need to classify and weight expert's opinion appropriately. Similarly, Sorvari and Seppälä (2010) found that a reduction in the weighting of their single cost criteria (Table 1) did cause some of the remediation alternatives with lower risk reduction values to be preferentially selected. This was significant as decision-makers could be unwilling to accept this cost-reducing trade-off as the primary aim of the remediation is to significantly lower or eliminate the risk posed by the contaminant (Alexandrescu et al., 2014). These two studies (Li et al., 2018; Sorvari and Seppälä, 2010) demonstrate the importance of applying professional judgement when using the outputs of a DSS, and appropriately weighting criteria (cost in this case) (Table 1).

DSSs have also been developed to assess the sustainability of remediation methods e.g. the Sustainable Choice Of REmediation (SCORE) DSS (Rosén et al., 2015, 2013; Söderqvist et al., 2015). Remediation method selection in SCORE uses the three components of sustainable development: Environmental, Social, and Economic (Brundtland et al., 1987; UNEP, 2020). Rosén et al. (2015) defined a list of key criteria and sub-criteria to assess each component. SCORE is unique in that it gives equal weighting to social, economic environmental criteria. However, the SCORE method requires detailed project-specific data, including chemical concentrations, which depending on the stage of redevelopment is not always available (Fig. 1). Huysegoms and Cappuyns (2017) critically reviewed 13 DSSs (from both the private sector and the academic literature) used for assessing remediation sustainability, focusing on how they performed against six criteria based upon fifteen headline catagories identified by the Sustainable Remediation Framework UK (Bardos et al., 2011). Findings of this current critical review agree with Huysegoms and Cappuyns (2017) in that there is a need for greater consideration of the economic and social aspects for sustainable remediation. Eleven out of thirteen of the DSS reviewed by Huysegoms and Cappuyns (2017) only partially consider economic and social criteria. Additionally, the value of enhancing user-friendly experience when manipulating input data and outputs is also recognised by Huysegoms and Cappuyns (2017). Improving the consideration of socioeconomic variables within DSS research will allow them to become adaptable for a variety of project types alongside increasing the understanding of influence of socioeconomic constraints on brownfield redevelopment.

Only one of the DSSs reviewed was designed to focus estimating remediation method costs. Kaufman et al. (2005) uses an empirical model to estimate remediation costs for brownfield and contaminated sites. Detailed chemical concentrations and data on volume of the

Table 1
Summary of remediation technology selection DSSs. BGS © UKRI 2021 and Cranfield University © 2021.

Author(s)	Year	DSS name	MCDA method	Redevelopment stage	Environmental criteria	Social criteria	Economic criteria	Other criteria
Hokkanen et al.	2000	n/a	SMAA-2	Post-site characterisation	Environment	n/a	Cost Credibility of the offer	Innovation Project management
Salt and Dunsmore	2000	n/a	Goal programming	Post-site characterisation	Soil erosion and sedimentation, soil organic matter, soil nutrient transport to water, soil pollutant transport to water, ammonia emissions, biodiversity, landscape quality, agricultural product quality, agricultural product quantity, animal welfare	n/a	Agricultural product quality, agricultural product quantity	n/a
Nasiri et al.	2007	n/a	Fuzzy-WSM	Post-site characterisation	Contaminants Soil types	n/a	n/a	Time Durability
Promentilla et al.	2008	n/a	Fuzzy-ANP	Post-site characterisation	Environmental effectiveness	Social acceptability	Financial affordability	Implementability
Bello-Dambatta et al.	2009	n/a	AHP	Post-site characterisation	Technical efficacy Wider environment Waste by-products	Societal considerations	Cost-effectiveness	Regulatory obligation
Pizzol et al. Critto and Agostini Carlon	2009	DESYRE	AHP (in Decision Module)	Post-site characterisation	Residual risk extension, residual risk magnitude, risk magnitude reduction, technological set quality, environmental impact	Socioeconomic impact	Cost	Logistical set quality Time
Purucker et al.	2009	SADA	n/a (GIS Analysis)	Post-site characterisation	Chemical benchmarks Ecological benchmarks Benchmark screens Exposure model Risk mapping Site scale Volume estimates Probability maps	n/a	n/a	n/a
Sorvari and Seppala	2010		MAVT	Post-site characterisation	Groundwater quality, ecological risk, health risks, emissions to air, energy consumption, soil loss, groundwater loss, space use, waste generation, ecological impact	Image impact	Economic impact	n/a
Yatsalo et al.	2012	DECERNS	MAVT, AHP, TOPSIS and PROMETHEE, MAUT, ProMAA and fuzzy criterion weightings	Post-site characterisation	Current land use Radiological data Residual risk	Improvement of psychological wellbeing Improvement of social-economic wellbeing	Cost	Local produce consumption Population densities
Rosen et al. Soderqvist et al.	2015	SCORE	SCORE	Post-site characterisation	Soil, flora and fauna, groundwater, surface water, sediment, air, non-renewable natural resources, non-recyclable waste	Local environmental quality and amenity Cultural heritage Equity Health and safety Local participation Local acceptance	Social profitability	n/a
Bai et al.	2015	n/a	AHP-TOPSIS	Post-site characterisation	Environment impact	Acceptability	Overall cost Resources demand	Development status Applicability Clean-up time
Li et al.	2018	n/a	Modified AHP	Post-site characterisation	Possibility of secondary contamination Risk of human security Public acceptability	n/a	Equipment cost Operation cost Detection and analysis cost	Remediation efficiency Remediation time Technological maturity
Li et al.	2018	n/a	AHP-PROMETHEE	Post-site characterisation	Residual risk Reduction rate	Approval and acceptance	Equipment investment Operational maintenance cost	Operability Remedial duration Long-term operational stability Supervision difficulty Reuse difficulty Compatibility

contamination are needed, therefore this model can only deliver effective outputs when detailed site-characterisation studies have been carried out, which is typically later in the development process (Fig. 1). Accurate cost estimates can be advantageous in the early stages of site development and remediation (Fraser et al., 2018) helping to counteract delays caused by unknown ground constraints (Ameller et al., 2020; Connaughton and Mbugua, 2008; Male, 2008). The value of early-stage remediation cost estimates is demonstrated by the award-winning Brownfield Ground Risk Calculator (BGR_calc) (British Geological Survey, 2019). Cost estimates for remediation of soil and groundwater contamination in this emerging tool are based on published guidance (Homes and Communities Agency, 2015).

Overall, there are several types of DSSs considering a wide range of factors that influence the selection of remediation methods. The majority are dependent on the inclusion of accurate data inputs that are collected during site investigation and characterisation (e.g. concentrations and spatial distribution of contaminants), which are not always available in earlier stages of the decision making. In addition to this, the majority of the DSSs in this section focus on environmental and contamination issues, neglecting the socioeconomic dimension of sustainable remediation (Smith, 2019).

2.2. Land use suitability and site prioritisation

Twelve DSSs designed to inform future land use suitability for brownfield sites were reviewed (Table 2). Land use suitability DSSs are designed to support planning professionals, mostly using MCDA and GIS to enhance the value of using environmental and planning datasets. Two types of DSSs were distinguished: (1) those that seek to assign suitable land uses within and between sites and (2) those that are designed for site prioritisation. In a manner analogous to the remediation methodology selection, many of these DSSs utilise detailed, post-site investigation data/information (Table 1). Land use suitability is evaluated at different stages of site redevelopment including master planning and after detailed site investigation and risk assessment (Fig. 1). The development stage dictates data/ information required by the DSSs. As might be expected, DSSs that evaluate land use suitability, post-site investigation, rely on such data (Table 2). DSSs used for strategic planning take a broader approach by accounting for a wider range of considerations including social and economic benefits during early stages of development (Huysegoms and Cappuyns, 2017).

2.2.1. Land use suitability

Herbst and Herbst (2006) use a GIS-integrated weighted sum model (WSM) to evaluate brownfield site suitability for redevelopment as urban wildlife areas, focusing solely on environmental planning constraints. Culshaw et al. (2006) had similar objectives but recognised that planning decisions are influenced by other factors, like value of redeveloped land. This siloed approach to brownfield DSSs ignores the potential to provide better support to the end-user by evaluating sites holistically and taking into account other factors including social and economic considerations.

Schädler et al. (2011, 2012 and 2013) implemented a spatial algorithm to automate the assessment of land use options based on development sustainability indicators. Schädler et al. (2011, 2012 and 2013) used a dual assessment of remediation options and land use suitability designations to inform their outputs. Their work demonstrated that with their tool, stakeholder discussion can be efficiently incorporated into the DSS during the planning application stage of the development. In addition, by setting the DSS to derive proposed land use classification, their approach was reported by Schädler et al. (2013) to streamline the selection of land use types for complex sites for their case study area. However, this approach may not be suitable for every case. For example, on sensitive sites or sites where difficult trade-offs need to be considered (e.g. cost saving vs residual risk (Syms, 1999)), land use options produced automatically might not be appropriate as they might not have accounted for ad-hoc real-world variability. The Schädler et al. (2011, 2012 and 2013) approach does, however, achieve one of the major purposes of a DSS; to provide more information to support expert evaluations. A large proportion of the site-specific data required by the Schädler et al. (2011, 2012 and 2013) approach may not always be available or may come too late in the planning process to provide useful application in early-stage examples. This may challenge the transferability and applicability of this methodology and system outside of data rich, late-stage brownfield projects.

Socioeconomic assessment criteria are more commonly used in land use planning DSSs (Table 2) than other applications. However, the uncertainty of these criteria weighting and decision analysis methods is generally greater due to their subjectivity (Agostini et al., 2009). To deal with uncertainty, some land use planning DSSs use MCDA methodologies integrated with fuzzy/rough set mathematical operators. For example, Chen et al. (2011) demonstrated that using a GIS-based Ordered Weighted Average (OWA) method together with an AHP pairwise comparison produced land use classifications that can inform effective land use planning decisions. Similarly, Mosadeghi et al. (2015) developed land use classifications using both AHP and Fuzzy-AHP spatial MCDA methods to the same end. The findings of Mosadeghi et al. (2015) confirmed the findings of Kordi and Brandt (2012) that Fuzzy AHP is less sensitive to criteria weight changes. This adds credibility and weight to decision making because it addresses uncertainties associated with weighting input parameters and their role in influencing the outputs.

There is only one example in literature of a predictive modelling algorithm being used within a brownfield land use suitability DSS. Liu et al. (2019) used a Presence and Background Learning machine learning method to assess the redevelopment suitability of brownfields in Shenzhen, China. This used crowd-sourced datasets and a Web-Crawler to aggregate planning data and urban population dynamics at both site and building scale. Liu et al. (2019) were able to collate and utilise this socioeconomic information and live data for decision-support more efficiently and in greater detail than previously possible, with conventional decision analysis.

Similarly to Liu et al. (2019), Beames et al. (2018) and Abdullahi and Pradhan (2016) developed methods that utilise mainly socioeconomic analysis to inform potential location and land use of brownfield site for redevelopment in Belgium (Beames et al., 2018), and Malaysia (Abdullahi and Pradhan, 2016). These two DSSs address how residents of a local area will benefit post-development, particularly in relation to access to social amenities (Beames et al., 2018). It was suggested by the authors that future work could focus on integrating future land use predictions to account for population increase and using predictive models to evaluate long-term sustainability and change over time.

Incorporation of stakeholder preferences, is more common for land use suitability DSSs than for remediation technology selection DSSs. There is an identified need for ongoing, comprehensive stakeholder analysis during the design stages of DSSs to account for stakeholder needs and preferences (Tendero and Plottu, 2019). However, incorporating stakeholder attitudes, opinions and preference into a DSS can prove difficult, as there is no single defined means to achieve this, perhaps suggesting the need to develop a general, widely applicable workflow. To tackle this issue, Burinskiene et al. (2017) established the relative weights of criteria by combining stakeholder judgement of brownfield redevelopment issues with a MCDA ranking methodology. Their study concludes that the most important criteria for brownfield redevelopment (as determined by their stakeholder/MCDA ranking) are: (1) investments in infrastructure, (2) green areas per inhabitant, (3) cost of new real estate, (4) areas of empty sites per inhabitant and, (5) pollution from heavy industry. These results are informative and useful, however they may lack validity when applied to external examples due to: (1) the relatively small sample size of 12 stakeholders (in comparison to other brownfield DSS stakeholder campaigns where many 100 s of responses are required (Rizzo et al., 2015)), and (2) the stakeholders used to define a shortlist of criteria were recruited from one city region (Vilnius, Lithuania). Further research is needed to effectively evaluate and incorporate stakeholder involvement into brownfield land use planning DSSs.

2.2.2. Site prioritisation

When decisions about a portfolio of brownfield sites are needed, decision-makers must analyse pertinent information and to sort, prioritise, and select sites for development based upon defined criteria or needs (Burinskiene et al., 2017). There has been a significant increase in the availability of planning data and implementation of high-level spatial planning in the past decade or so (Crook and Whitehead, 2019), that is supported by recent digital planning reform in the UK (MHCLG, 2020). This is facilitating a change from traditional paper-based planning system to an innovative data-driven process which allows planners and developers to make use of data in ways that were not previously possible.

Two key tools for the ranking of brownfield sites are reviewed below, the SYRIADE DSS and the TIMBRE Brownfield Prioritisation Tool. These were selected as they are recognised as influential DSS projects within the brownfield development literature. Table 3 presents a comparison of key features of TIMBRE and SYRIADE.

2.2.2.1. SYRIADE. The Spatial decision support SYstem for Regional rIsk Assessment of DEgraded land (SYRIADE) (Agostini et al., 2012; Pizzol et al., 2011; Zabeo et al., 2011) combines a vulnerability assessment with a 'regional risk estimation' for every site within a portfolio, in order to generate a risk score for the explicit purpose of ranking contaminated sites (Agostini et al., 2012; Pizzol et al., 2011; Zabeo et al., 2011). The risk score produced is based on the commonly used 'Source-Pathway-Receptor' or S-P-R model. This is a product of three expert weighted variables: (1) hazard score for the source of contamination, incorporating understanding of toxicity, (2) scores that parameterise the contaminant exposure pathways, and (3) vulnerability scores for the receptor. This approach of assigning scores to sources, pathways and receptors is similar to the emerging UK-based DSS BGR_calc (British Geological Survey, 2020). Zabeo et al. (2011) present a vulnerability assessment for: human health, groundwater, protected areas, and surface water; where each is assessed against several attributes with each being assigned a score. Using a linear weighted average MCDA method, the receptor vulnerability for an area can be assigned aggregating scores. These scores are then converted using an attribute specific spatial aggregation function in GIS software. The scores are then used in the subsequent risk assessment module of SYRIADE (Pizzol et al., 2011) which presents a unique approach to integrating a conceptual site model into a decision support system within a GIS environment.

Agostini et al. (2012) is the third and final article in the series and reports on the development of the SYRIADE SDSS interface, integrating groundwater vulnerability and risk assessment modules (Pizzol et al., 2011; Zabeo et al., 2011) with a socioeconomic assessment and integrated decision analysis. The socioeconomic assessment is calculated using a simple weighted sum model MCDA using the following criteria: (1) population density, (2) land use, (3) GDP per capita compared to the community average from the last 3 years, (4) unemployment compared to EU average, and (5) density of railways and highways. This score is then used to assign a 'recovery potential' class (low, medium, high). The risk scores are either summed or averaged to generate a total risk score.

Agostini et al. (2012) suggest a number of improvements to SYRIADE, but these are equally relevant to many brownfield DSSs. They suggest improving the Graphical User Interface (GUI), a web-server to allow multiple stakeholders to contribute to weightings. They also advise that sensitivity analysis should be conducted in order to explain the influence of different factors on the overall risk assessment result. Additional evaluation of SYRIADE is provided by Pizzol et al. (2011) where they state that SYRIADE is flexible and easily adaptable to different regional context and regional data availability. However SYRIADE, like many others, is reliant on availability of late-stage site-specific data relating to contamination. While SYRIADE is a site ranking DSS for strategic planning, site-specific data are unlikely to be readily available, accurate, and/or suffer from considerable regional heterogeneity at this stage of development (Panagos et al., 2013). This means that the approach taken by SYRIADE may not always be practical or effectively implemented for most planning stage portfolio ranking for brownfield sites.

2.2.2.2. TIMBRE. Pizzol et al. (2016) present the Tailored IMprovement of Brownfield Regeneration in Europe (TIMBRE) Brownfield Prioritisation Tool. This web-based modular spatial DSS was designed to rank a portfolio of brownfield sites based upon user-defined and user-weighted inputs. Inputs were categorised into dimensions (e.g. social) formed of factors (e.g. transport links) and indicators (Criteria) (e.g. proximity to metro stations). Collectively these parameters were then weighted by the user. Normalisation and aggregation of these components by means of convex combination (CC) was conducted, with Ordered Weight Average (OWA) method being used to generate a final score for each site. Fig. 3 taken from Pizzol et al. (2016) shows the hierarchical structure of TIMBRE's MCDA ranking methodology.

TIMBRE is applied to a pilot case study area in the Czech Republic and used to rank a selection of brownfield sites for redevelopment as either a shopping centre or a solar power plant. In this example, three dimensions with sub-factors comprised of multiple indicators were defined. The three dimensions used were: (1) local redevelopment potential, (2) site-attractiveness and marketability, and (3) environmental risk. TIMBRE is designed with these three top-level criteria as default, but they can be overridden if desired. Weightings for all dimensions, factors and indicators were determined using local expert input. The advantage of the TIMBRE approach is that scale and complexity of the assessment and ranking is determined by the user/ stakeholders. This means it is flexible and can be iteratively applied to range of brownfield decision making problems (Bartke et al., 2016) to suit local context based on expert judgement and availability of information. The TIMBRE tool is evaluated in Bartke et al. (2016) based on feedback from users. Their evaluation is summarised using the SWOT framework (Madsen, 2016) for user feedback, and also evaluated against sustainability principles for DSSs (Bartke and Schwarze, 2015). One key shortcoming of TIMBRE, is the objectivity of results of the tool (Bartke et al., 2016; Rizzo et al., 2018). Bartke et al. (2016) state that in order to overcome this, clear communication of weightings and evaluation dimensions is needed between internal expert users and stakeholder and end-users. Two other shortcomings of TIMBRE are the insufficient attention and detail around contamination issues in that there is no built-in mechanism to assess contamination, and the interoperability of TIMBRE with other software applications needs to be addressed (Bartke et al., 2016).

Features of TIMBRE and SYRAIDE are compared in Table 3. Each DSS achieves an effective site ranking for decision-makers to use, however, they achieve it in two different ways. SYRIADE provides a detailed assessment of sites, including regional risk assessment and vulnerability assessment, taking into account a variety of factors that are typically fixed. SYRIADE users can, however, add additional factors or modify proposed factors, as long as they identify the related classes the factors belong to. On the other hand, TIMBRE is a very open DSS, while the assessment framework is fixed, the assessment criteria are user dependent. Neither option is necessarily better than the other as there are advantages and disadvantages to both. On the one hand, having a rigid highly detailed DSS, like SYRIADE, can provide stakeholders with answers to specific questions, but only those questions. Whereas a more open DSS, like TIMBRE, can help to solve more dynamic problems, but requires the users to fully understand the question and its component parts to produce high-quality, reliability outputs.

Table 2
Summary of land use suitability DSSs. BGS © UKRI 2021 and Cranfield University © 2021.

Author(s)	Year	Spatial DSS	Methods	Redevelopment stage	Environmental criteria	Social criteria	Economic criteria	Other criteria
Chen et al.	2009	No	Dominance-based rough set approach	Post-site characterisation		Jobs created during redevelopment	Conservative estimate tax revenue, tax gained, optimistic estimate tax revenue, tax gained, actual tax revenue, tax gained	Number of redeveloped brownfield sites, area of redeveloped brownfield sites, number of in-progress brownfield sites, area of in-progress brownfield sites
Chen et al.	2011	Yes	GIS ordered weighted average, AHP	Post-site characterisation	Goaf collapse Karst collapse Earthquake	Access to public transportation		Site type
Mosadeghi et al.	2015	Yes	AHP, Fuzzy-AHP	Planning stage	Avoid proximity to valuable ecosystems, floodplain areas, fire hazard areas, storm surge, accessibility to the broadwater, proximity to waterways and water bodies, proximity to natural protected areas	Avoid scenic routes	Proximity to one of the existing growth corridors, proximity to retail and commercial areas, avoid proximity to industrial development, avoid good quality agriculture land, avoid intact key resource areas	Power supply, access to road network, access to haulage routes, water supply, reliability of water resource, sewerage, proximity to existing marine precincts, avoid urban (residential areas), sewerage pump out facilities
Liu et al.	2019	Yes	Presence-and-background learning (PBL)	Planning stage	Elevation, slope, former land use type, size of land parcel, plot ratio	Medical facility density, educational facility density, recreational facility density, restaurant density, shopping facility density, government agency density, financial services density, enterprise density, distance to district centre, distance to park/open space, distance to water area/ coastline	Property value, land value	Building stories, architectural structure, building age, road accessibility, peak time population, population per hour in a weekday, population per hour in a weekend, peak time population density
Culshaw et al.	2006	Yes	GIS analysis	Planning stage	Groundwater protection, flood risk, drainage, land contamination, proximity to landfill, biodiversity	Natural and man-made heritage		
Herbst and Herbst	2006	Yes	GIS analysis	Planning stage	Size, located in wildlife deficiency area, importance for greenspace network, surface sealing, water features	Population density, access from schools Access from bike paths		Accessibility, penetrability, safety, diversity of structures, diversity of successional stages
Abdullahi and Pradhan	2015	Yes	GIS, weights of evidence	Planning stage	Distance from agricultural fields, soil and geology properties, distance from flood zones	Proximity to public transportation facilities, proximity to recreation facilities, proximity to community facilities, population density, residential density		Proximity to infrastructure, proximity to road networks, proximity to same land use types, built up density, land use diversity
Beames et al.	2018	Yes	GIS analysis	Planning stage		Travel distance to doctors, travel distance to pharmacies, travel distance to employment, travel		

						distance to schools, travel distance to green spaces, travel distance to meeting places, travel distance to shops		
Burinskiene et al.	2017	Yes	GIS, AHP	Post-site characterisation	Soil contamination, heavy industry pollution, green areas, transport pollution	The level of unemployment, the level of poverty, household incomes, the level of public crimes, access to educational institutions	Infrastructure investment, cost for new real estate, number of projects funded by EU, number of workspaces	Empty sites, number of schools, state and average age of new constructions, magnitude of new constructions, distance to the city centre
Schadler et al. Morio et al.	2011 2012 2013	Yes	Bespoke assessment algorithms	Post-site characterisation	Contaminated area requiring soil remediation, contaminant concentration matrix for soil, contaminant concentration matrix for groundwater, conflict matrix for soil contaminants, conflict matrix for groundwater contaminants, contaminated area requiring soil remediation, contaminant concentration matrix for soil, contaminant concentration matrix for groundwater, conflict matrix for soil contaminants, conflict matrix for groundwater contaminants, total number of contaminants considered, number of contaminants in soil considered, compliance criteria matrix soil contaminants, compliance criteria matrix groundwater contaminants, number of contaminants in groundwater considered, contaminated soil volume requiring remediation, site contains <40% sealed soil, site location within urban area, site is part of a local habitat, high value tree or plant populations, site strongly contaminated	Residential areas in the surrounding area, green spaces in the surrounding area, local supplies within walking distance, neighbouring uses are strongly pollution emitting, direct vicinity to nature reserve, low capacity of access roads, good access to public transport, access to clearway Good accessibility for bikers, local amenities in walking distance, primary school in walking distance, great impact on recreational areas, historically relevant buildings, great influence on cityscape	Suitability matrix, suitability value, reference land value vector, indices for planning unit, x-value, y-value, contaminant, and land use, land value matrix, remaining land value matrix, maximum land value vector, difference to remaining land value, remediation cost matrix, site preparation cost vector, site suitable for innovative industries, adjacent enterprises w/ precarious sense of security	Planning unit area vector, number of land use types considered, number of planning units, location quality matrix, land use matrix, number of raster rows, number of raster columns, neighbouring uses sensitive to emissions, good supply and disposal infrastructure
Odii et al.	2019	No	WeValue stakeholder engagement	Post-site characterisation	Air emission soil & ground conditions Groundwater & surface water ecology Natural resources & waste	Human health & safety ethics & equality, Neighbourhood & locality Communities & community involvement compliance, Uncertainty & evidence Air	Direct economic costs & benefits, indirect economic costs & benefits, employment & employment, capital induced economic, costs & benefits, project lifespan & flexibility	
Bardos et al.	2016	No	Brownfield opportunity matrix	Planning stage	n/a	n/a	n/a	n/a

Table 3
Comparison of TIMBRE and SYRIADE features. BGS © UKRI 2021 and Cranfield University © 2021.

DSS	Spatial DSS	Methods used	Types of output data	Redevelopment stage	Environmental criteria	Economic criteria	Social criteria	Temporal analysis	Uncertainty analysis	User friendliness	Stakeholder involvement
SYRIADE	Yes	MCDA (multi-attribute value theory) Bespoke risk estimation equation	Fixed-recovery potential score, R_NUT risk score, integrated management class, spatial representation (Maps)	Planning stage	11	2	3	No	No	Poor user interface	Yes – small amount of stakeholder analysis
TIMBRE	Yes	MCDA (ordered weighted average, convex combination)	User dependent - tabulated scores, spatial representation (Maps)	Planning stage	5[a]	9[a]	8[a]	No	No	Poor user interface	Yes – comprehensive stakeholder analysis

[a] TIMBRE criteria quantified here are from Pizzol et al. (2016) case study used to illustrate typical TIMBRE criteria for brownfield projects.

2.3. Land use sustainability assessment

Land use sustainability assessment is characterised by placing an emphasis on clear communication with stakeholders, this is reflected in the DSSs reviewed. Odii et al. (2019) investigated the integration of the SuRF-UK sustainability framework (Bardos et al., 2011) with a specialised values-based software called WeValue InSitu (University of Brighton, 2016). They assess the sustainability of land use decision making, keeping stakeholder views and preferences at the centre of the decision-making structures. The WeValue process is used as a 'bolt-on' process that produces localised social indicators which are added to the 'Assessment Indicators' stage of the SuRF-UK process. The inclusion of stakeholder preferences in this way has three main advantages: (1) it provides indicative local society attitudes, (2) it limits issues to a predetermined lists without opportunity for new issues to be added, (3) and allows for wider participation and transparency when accounting for stakeholder opinions in sustainability assessments.

Similarly, Bardos et al. (2016) present a non-spatial, non-software integrated assessment framework designed for stakeholders to oppose, estimate and discuss the value soft re-use of brownfield sites (i.e. not based on built constructions or infrastructure). Their framework has four major components: (1) the brownfield opportunity matrix that can identify potential soft re-uses and their value, (2) using sustainability linkages in the creation of a conceptual site model (CSM), (3) using the CSM to provide a framework for sustainability and cost effectiveness assessments (through cost-benefit analysis), and (4) using these assessments to understand the value of soft re-use. Their methodology allows for stakeholders to attribute value to the often intangible costs and benefits of soft re-use development. As a secondary benefit, the method demonstrates that soft re-use of brownfield sites can easily achieve sustainability targets and satisfy stakeholders concerned with monetisation of developed land, supporting earlier discussion on the benefits of varied land use types for brownfield sites.

The methodology of both Bardos et al. (2016) and Odii et al. (2019) demonstrate good practice in the conduct and implementation of stakeholder analysis for the creation of brownfield DSSs. They could be used as a framework for the inclusion of stakeholder preferences in future holistic DSSs that assess not only stakeholder perceptions and needs,

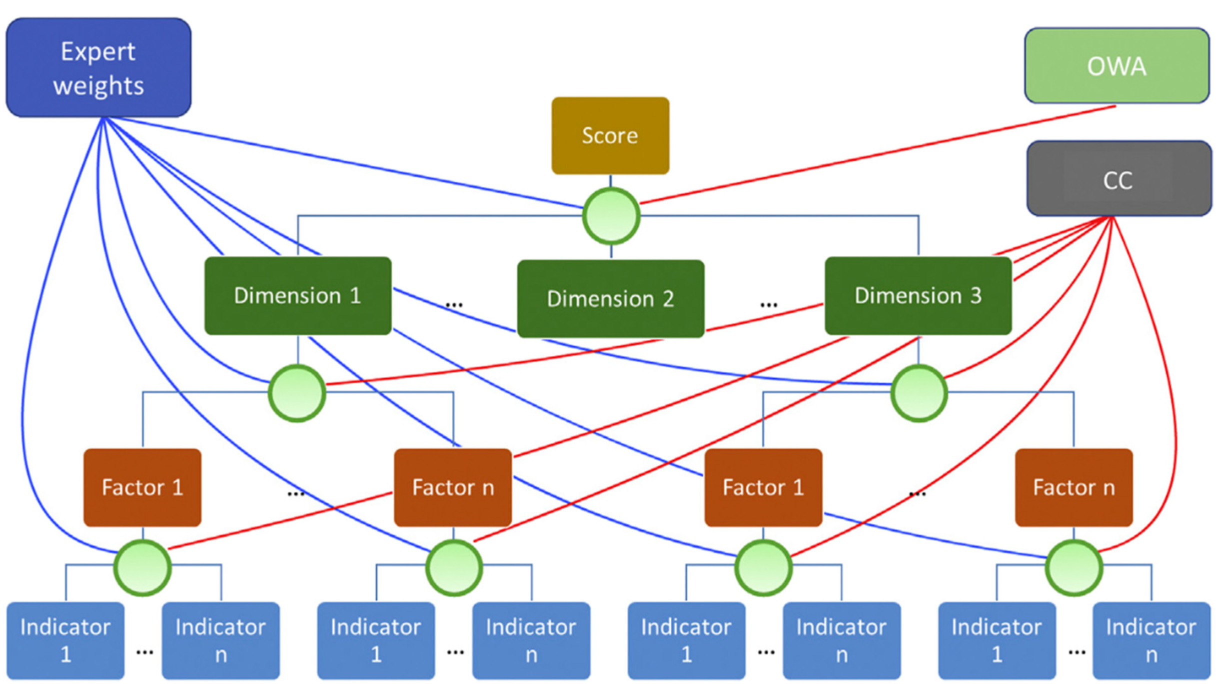

Fig. 3. MCDA Hierarchy of TIMBRE, from Pizzol et al. (2016).[1] [1]Reprinted from Journal of Environmental Management, 166, Pizzol et al., Timbre Brownfield Prioritisation Tool to support effective brownfield regeneration, 178–192, Copyright (2016), with permission from Elsevier.

but also key environmental and contamination risks which are balanced with economic factors.

Bartke and Schwarze (2015) presented a review and general commentary on the quality of sustainability assessment (SA) DSSs when applied to brownfield land use planning. They examined the trade-offs between a DSS's ability to account for sustainability principles and their effectiveness in decision making. They used a set of assessment criteria established during a workshop: objectivity, transparency, practicability, participation needs [to be able to use the DSS], flexibility, and [the ease of] institutional embedding. User requirement assessment criteria were weighted against three typical user groups: the public, expert consultants and decision makers. They reviewed three SA DSSs: RESCUE (RESCUE, 2004), SINBRA SAT (Bittens et al., 2008), and the Soil Value Balance (SVB) decision support model (Doetsch et al., 1998). They concluded that each tool reflected a different strengths for the assessment criteria of the Bellagio Sustainability Assessment and Measurement Principles (BellagioSTAMP) (Pintér et al., 2012). The SVB model was shown to be the best-rounded tool, RESCUE being strongest for participation, and SINBRA SAT allows for the greatest flexibility and practicability. Bartke and Schwarze's (2015) research again highlighted the need for detailed stakeholder and user group analysis prior to the development of DSSs. Their findings suggest that there is no 'perfect tool', and that trade-offs should be fully understood by users when applying these tools. None of the tools assessed scored highly for institutional embedding (ease of adoption by an institution) for any of the user groups. This suggests that in order to truly meet a user's needs, a tool should be designed, or at least be able to be amended, on a case by case basis.

3. Future opportunities for DSS

In this review, we have presented a large amount information on DSSs with the aim of synthesising current progress and developments in decision support systems for brownfield redevelopment applications. To date, there are several types of DSSs addressing a variety of issues including remediation technology selection, land use planning and sustainability. The strengths and limitations identified in the literature have been discussed in Section 2 and are used to inform key points of discussion in the following sub-sections. These key considerations have informed the current authors' future research and development needs for DSS.

3.1. Socioeconomic issues

Socioeconomic considerations are underrepresented in the brownfield DSS reviewed. The focus of the majority of site characterisation, remediation and land use suitability DSSs is on the environmental and contamination components of redevelopment. Socioeconomic aspects are mainly considered in DSSs designed evaluate the overall sustainability of remediation and development schemes, accounting for all three dimensions of sustainability (social, economic and environmental). This is also true for DSSs designed to evaluate the sustainability of land use decision making from a socioeconomic and stakeholder point of view (Bardos et al., 2016; Odii et al., 2019).

The need for greater consideration of social and economic dimensions into DSSs for brownfield redevelopment is acknowledged by a range of authors including Bardos et al. (2016), Beames et al. (2018), Green, 2018, Huysegoms et al. (2019) and Huysegoms and Cappuyns (2017). The absence of sustainability considerations in DSSs designed for risk-based mitigation of contamination issues is likely to be because issues of this type often pose an immediate risk to receptors and the reduction of these risks (Bardos et al., 2011).

Consideration of socioeconomic issues is more prominent in recent DSSs (Bai et al., 2015; Beames et al., 2018; Odii et al., 2019; Rosén et al., 2015; Tendero and Plottu, 2019; Zhu et al., 2015). However, as discussed by Huysegoms and Cappuyns (2017) these still under appreciate some socioeconomic factors, in particular detailed analysis of economic factors (Ameller et al., 2020). This is supported by findings of this review where only one of the articles reviewed (Kaufman et al., 2005) focused specifically on developing cost estimates for brownfield site remediation. A criticism that can be made of many other DSS research incorporating economic factors lack detail in their generation of economic appraisal information or simply attribute it to expert valuation. The need for better integration of economic considerations into brownfield research is also recognised by a recent review paper (Ameller et al., 2020) that further highlights that there is significant scope for improvement. The current authors suggest that the dedicated investigation of the influence and role of socioeconomic/economic factors in brownfield redevelopment be an area of future DSS research to provide a more balanced approach to decision-making.

3.2. Geographical scale versus development stage

Most of the research reviewed focuses on site-specific brownfield decision making problems later in the planning and development process (i.e. post-detailed intrusive site investigation and remediation technology selection) (Fig. 1). As discussed in Section 2, the most common application for DSS to address is the selection of a site-specific remediation technology, only sometimes is this simultaneously carried out for multiple sites (Van Der Perk et al., 2001). DSSs for selecting site-specific remediation options are dependent on detailed site-specific data and information, usually acquired during the intermediate or late stages of a project. DSSs focusing on land use planning applications are typically for a range of scales and stages of development, but still predominantly local scale and late-stage. The trend for DSSs to address late-stage site-specific problems makes sense; the functionality of DSS is better supported, with detailed data about site(s) (Black and Stockton, 2009). However, this is somewhat a paradox. Uncertainty and unknowns regarding ground conditions typically decreases further along the investigation/development process (Fig. 1), so it stands to reason that useful decision-support tools could be more impactful in supporting decision makers during strategic/master planning or project cost-benefit evaluations.

A DSS has the capacity to aid the screening and assessment of sites, but not without challenges. At the preliminary risk assessment/ initial desk study phase of a project a contaminated land specialist will draw together multiple sources of information, from a combination of publicly and privately held resources. This can generally be purchased as a data bundle from a commercial data reseller. A DSS has the possibility of automating this process, reducing the time to complete such studies. This could be highly beneficial in time critical due diligence projects, which often require the assessment of vast amounts of information in a short period of time and within the early stages of planning and development where screening the suitability of a portfolio of sites could enhance the quality, transparency and timeliness of development plan-making and decision making.

The data reviewed within desk studies can vary in its ease of use in DSSs, some sources such as historical maps require interpretation based on knowledge and experience, where as other datasets may be available in numerical format (chemical data or groundwater data) or prescribing certain properties (aquifer status). The second phase of investigation involves intrusive ground investigation provides numerical data relating to chemical, geological, hydrogeological and geotechnical characteristics which has associated geospatial parameters and can be more readily inputted into a DSS. The following remediation phase of the project requires the selection of remediation techniques and the formulation of cost estimates. While the former has been demonstrated in other DSS, the economic considerations are dependent on costs which may vary significantly on location and external economic factors.

DSSs may be best placed to aid early stage decision processes, selecting candidate sites from a portfolio and explaining concepts and risks to non-experts and wider stakeholders, allowing DSSs move into a previously unoccupied area of support for decision makers.

3.3. Data, methods and platforms

A well-designed graphical user interface (GUI) is needed to communicate the data and information produced by a DSS to users and stakeholders (Huysegoms and Cappuyns, 2017). Two of the DSSs reviewed here developed bespoke GUIs specific to their DSS (Pizzol et al., 2016; Schädler et al., 2013). These user interfaces are quite simple and functionally similar to a standard GIS viewer, allowing users to see calculated and mapped outputs as single or multiple attribute layers with limited interactivity. User feedback from the TIMBRE project highlighted the need for better interoperability of the DSS with commonly used software (e.g. GIS) (Bartke and Schwarze, 2015). This would mean that the DSS outputs and datasets are derived in a way that they mean they are interoperable with other software environments. Users also requested better data interrogation tools, able to view attributes and inner functions of the model (Bartke et al., 2016). These remarks are also mirrored in suggested improvements for the SYRIADE DSS (Agostini et al., 2012), whereby an GUI hosted on a web-based platform could have improved stakeholder analysis and engagement.

WebGIS (e.g. Google Maps) is now commonplace in today's world, with most people in developed economies using it every day in one form or another for maps or navigation purpose (Peterle, 2018). The use of WebGIS viewer as GUIs and stakeholder communication tools is recognised in literature across disciplines (Culshaw et al., 2006; Horigan et al., 2018; Kong et al., 2015; Limasset et al., 2017; Yatsalo et al., 2012). However, WebGIS viewers are rarely fully integrated in DSS for brownfield applications. Over the past decade, advances in the functionality and usability of Web-Based GIS (e.g. ESRI's ArcGIS Online) which allow a larger range of geoprocessing tools to be available to the user as a complement or substitute to desktop GIS software (Kong et al., 2015; Kunapo et al., 2005; Peterle, 2018). This also means that users can access the GIS without proprietary software constraints (e.g. Leaflet – a JavaScript library for interactive maps). Furthermore powerful visualization tools for spatial data are not becoming widely adopted by the geospatial community e.g. ESRI's ArcGIS StoryMaps (ESRI, 2020). These tools allow map viewers to be embedded in scrolling webpages, allowing presentation of spatial data alongside explanatory text and a variety of other media to create a user friendly narrative. Features such as these should be used to full advantage, enabling better communication of DSS outputs and engagement of end-users. If integrated in brownfield DSS, these advances allow for the distribution of information to multiple-types of non-technical stakeholders, leading to an increased interaction with the data and subsequent understanding.

In the past few years, significant amounts of environmental and spatial data have been opened up in the UK, primarily from the Environment Agency (and regional equivalents) and Ordnance Survey. Open data releases and the rise of open source GIS programs such as QGIS now mean that basic spatial data analysis can be carried out by anyone with the interest to access it rather than being limited to those with the financial means to do so. However, as it stands, an individual or organisation cannot freely access the commonly agreed baseline data for brownfield desktop information which is necessary for any robust decision support tool. Again in the UK, the establishment and ongoing actions of the Geospatial Commission may be a catalyst for further opening up of the spatial data. Furthermore, key parts of data to inform DSSs such as historical land use, are only held by private companies and hence are unlikely to ever be available as open data. The implication being that DSSs are going to need to rely on both commercial and open sources of data. It is important to make the distinction between the availability of data for viewing, e.g. Web Map Services (WMS), and the ability to actually engage in meaningful analysis e.g. Web Feature Services or desktop data. There are a large number of view only data services available for environmental data, but unless they have suitable metadata and functionality for analysis built in by the data owner, a user is unable to curate and create their own analysis and DSSs. Existing available open data can also be subject to a number of reliability issues, including differences in resolution, coverage, accuracy, or a combination of these (Al-Sehrawy and Kumar, 2021; Vancauwenberghe and van Loenen, 2018). This can make the normalisation of different datasets within a common tool difficult. To overcome these issues, users and developers should account for limitations of open data and data infrastructure before utilising them within their DSSs.

The direction of travel is towards robust open data feeds, better interoperability, common data standards and increased transparency of methods, but this is still evolving and its value to brownfield redevelopment remains to be seen. Future research should work to integrate the fast-growing cloud-computing and real-time data streaming functions allowing stakeholders and users to attain a deeper more nuanced understanding to brownfield problems.

3.4. Predictive modelling

Only one of the DSSs reviewed applied predictive modelling in their DSS (Liu et al., 2019). The machine learning technique Presence and Background Learning was used to model optimum land use designations based on human population dynamics. Many DSS within the soil and groundwater sector are already using machine learning and predictive modelling methods successfully (El Bilali et al., 2021; Fathizad et al., 2020). The apparent lack of predictive modelling, including machine learning, within brownfield DSS research is surprising given modern computing capabilities, as well as the accessibility and ease in applying predictive modelling and machine learning algorithms (Kuhn and Johnson, 2013; Pollard et al., 2019). Predictive modelling and machine learning are already commonplace in several sectors including economics and finance, medical research, and engineering. Some example applications include image classification, forecasting stock prices, simulating recovery rates in patients, and modelling fluid dynamic systems (Kuhn and Johnson, 2013). Recent publications in contaminated land research do indicate the uptake of machine learning methods (Cipullo et al., 2019; Rodriguez-Galiano et al., 2018; Sajedi-Hosseini et al., 2018; Wu et al., 2013). Predictive modelling is also commonplace within other areas of environmental spatial analysis, such as assessing environmental impacts of herbicides (Kurina et al., 2019). However, brownfield decision-support research is so far missing the opportunity to utilise these innovations. Powerful prediction and forecasting algorithms could be used to address issues of future land use, population and environmental change, as well as migration of contaminants, site characteristics, or development costs. Data generated in remediation projects is often confidential, and not able to be shared for research purposes. Until this is overcome, the use of machine learning for remediation cost prediction may be difficult because obtaining sufficient data or sufficient quality is key to train and validate the models to make reliable predictions of remediation techniques and economics (Kuhn and Johnson, 2013).

To increase the confidence in predictive model outputs, uncertainties should be quantified. Sensitivity analysis describes how model inputs contribute to model outputs and can provide a powerful approach by helping to understand if the model is consistent with the conceptual ground conditions it is designed to reflect. Sensitivity analysis was not commonly reported in brownfield DSS literature, only two studies were found in this review (Mosadeghi et al., 2015; Promentilla et al., 2008). Both use sensitivity analysis to show that, in comparison to other MCDA methods, fuzzy-MCDA outputs are less susceptible to undesirable changes when input variable weightings are changed. The absence of predictive models and associated sensitivity analysis in the brownfield DSS literature reviewed is again surprising given its use in wider geoscience e.g. hydrologic, volcanic, and geomorphic modelling applications (Cannavó, 2012; Jefferson et al., 2015; Tucker and Whipple, 2002). To this end, the use of predictive models in brownfield DSSs may be a beneficial approach to constraining specific aspects of complex problems, such as changes in contamination over time or remediation cost estaimtes. However, any such approach should be combined with sensitivity analysis to maximise the likelihood of reliable and rational outputs.

Here we suggest the investigation of predictive modelling including machine learning methods as a key opportunity for future decision-support research for brownfield redevelopment. Such advances will see improved understanding of uncertainty, new insights, and faster analysis. These benefits will lead to increased confidence in DSSs results from both an environmental modelling and business analysis and planning standpoint.

4. Conclusions

This study has compiled, reviewed and evaluated literature on decision-support systems for brownfield land applications. The authors have identified a variety of applications and trends within brownfield DSSs as well as a number of shortcomings and opportunities. Remediation technology selection, land use suitability and land use sustainability assessment are the most common applications addressed by brownfield DSSs, most of which relying on MCDA and GIS analysis. There are a smaller number of studies assessing specific applications including; environmental risk assessment, stakeholder engagement, and vulnerability assessment. In general, brownfield DSSs focus on the assessment and quantification of environmental and contamination issues, during the post-site characterisation stage of redevelopment. General limitations identified by this research include: (1) the lack of quantitative socioeconomic criteria/dimensions within brownfield DSSs, (2) a tendency to focus on late stage redevelopment issues (such as remediation technology selection), (3) poor user interface and user experience within DSSs, and (4) low uptake of predictive modelling methods.

Three other considerations can be drawn from our review. Firstly, brownfield DSSs should be developed with intended users and stakeholders involved in the design and functionality of the DSS. Secondly, future research should provide increased detail surrounding economic appraisal within DSSs. However, confidentiality barriers over brownfield financial data will need to be overcome before significant progress can be made investigating economic variables of brownfield redevelopment within DSSs. Finally, a crucial area for future brownfield DSSs will be the increased assessment of the sustainability of land-use regeneration alternatives and remediation methods.

Key opportunities for future research include: (1) the integration of predicative modelling methods with sensitivity analysis into DSSs, (2) decision-support during the early stages of development, (3) brownfield DSSs addressing qualitative socioeconomic research, particularly economic considerations, and (4) great improvements in user interfaces, user-experience and web-based functionalities. Critical findings and suggestions put forward by this review should be combined with comprehensive stakeholder research to inform the future development of brownfield DSSs. These improvements would allow for DSSs to support brownfield redevelopment efforts and change the way brownfield ground conditions are understood early in planning and viability studies in the UK, Europe and across the world.

Limitations of this review: It should be noted that this review is limited to those DSSs reported in the academic literature between 1998 and 2021. Many more applications are expected to be in use by the private and public sector or may simply remaining unpublished (Rothstein and Hopewell, 2009). The first possible limitation is that the inclusion of articles over others is subjective, however papers were filtered based on relevance, using consistent standards. The second is that the findings are based on data that was collected from academic journals recorded in the Scopus database, a significant search of grey-literature or unpublished work was not carried out. In order to ensure that a large body of relevant literature had not been missed, a complementary search was carried out in Google Scholar and Web of Science. This served as quality control for the Scopus search, demonstrating that no additional relevant literature sources were available. Despite this, the review is considered to be comprehensive and includes all of the major developments in this field during the review period. The third possible limitation is the geographical representativeness of the research reviewed. As outlined in Section 2, the research reviewed is very Eurocentric. This indicates that either there is not a large volume of non-European research in this area, or, that research area from non-European research is not frequently reporting in the literature. Based on our review it is of the authors' opinion that the research is geographically limited. The final potential limitation is the time period considered. We used a 23-year time frame that is assumed to be representative of DSSs (brownfield and contaminated land) research because we believe a more recent coverage of the major journals to be more appropriate for this analysis, given the development and improvements in usability of computers and emergence of spatial data infrastructure over last two decades (Vancauwenberghe and van Loenen, 2018).

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CRediT authorship contribution statement

E. Hammond: Conceptualization, Methodology, Analysis, Investigation, Writing-Original Draft, Visualization, Data Curation. **R. Thomas, A. Kingdon, D. Hardy:** Writing-Review and Editing. **D. Beriro, F. Coulon, S. Hallett**: Project Administration, Validation, Analysis, Resources, Writing-Review and Editing, Supervision, Funding Acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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