Research article

The development of a novel decision support system for regional land use planning for brownfield land

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ABSTRACT

Digital tools, particularly specialised decision support systems (DSSs), can be utilized to assist in the complex process of brownfield redevelopment. Existing brownfield DSSs typically focus on site-specific, late-stage applications, and socioeconomic factors are often overlooked. In this paper, we present a novel DSS aimed at providing support for early-stage, city region-scale brownfield land use planning and redevelopment. The proposed DSS is a prototype WebGIS application that enables land use planners and other brownfield regeneration professionals to examine a region and a set of sites during the initial planning phase for brownfield redevelopment. The DSS includes three bespoke modules comprising: (1) Land Use Potential (residential, commercial, and public open space), (2) risks posed by contamination and geotechnical hazards, (3) data pertinent to brownfield economic viability assessments. We outline a use case for this DSS, developed through comprehensive user-requirements gathering, and subsequently describe the techniques employed to construct the DSS modules and user interface. Finally, we present the results of user testing, wherein case-study stakeholders assessed the DSS. The feedback obtained during user testing aided in the identification of areas for improvement with regard to the functionality, usability, and effectiveness of the DSS in supporting decision-makers. The feedback was utilized to implement iterative improvements to the DSS and to plan future developments for the prototype DSS.

1. Introduction

Brownfield land typically refers to sites and surrounding land that have been impacted by prior land use, which can result in contamination and often renders the location derelict or underutilized (CABERNET, 2006). According to estimates made in 2014, there are approximately 4.2 million brownfield sites across the European Union, out of which nearly 340,000 are predicted to need intervention prior to any redevelopment efforts (Van Liedekerke et al., 2014). The United States of America shares a similar scenario, with more than 450,000 brownfield sites deemed suitable for development (Green, 2018). In England, the potential for brownfield redevelopment is also recognized, with an estimated 23,000 brownfield sites (CPRE, 2022). The prioritisation of brownfield site development to alleviate urban land development pressures is an increasingly global phenomenon, often accompanied by specific national government policy measures (Green, 2018). For example, in England, the 2021 National Planning Policy Framework (NPPF) (MHCLG, 2021) and the Homes England Stratrgic Plan 2023 - 2028 (Homes England, 2023) both outline provisions that urge local planning authorities (LPAs) to support the reuse of brownfield land to meet housing demand. Furthermore, to incentivise the redevelopment of brownfield sites, governments often support redevelopment projects with grants and funding. For example, the UK Government has recently allocated £180 million as part of the Brownfield Land Release Fund (BLRF2) under the *One Public Estate* programme (LGA, 2023).

In addition to the pressing need for housing, brownfield sites are being redeveloped for a variety of purposes, such as the creation of blue/ green infrastructure and employment land, in accordance with a global

need for sustainable development, and environmental responsibility (European Union, 2010; The Land Trust, 2015; UNEP, 2020). In the UK, developers, local planning authorities (LPAs), and combined authorities (CAs) are encouraged to consider all possible land uses to meet sustainability and biodiversity objectives (MHCLG, 2021). Whilst brownfield redevelopment has potential benefits and support from governments, it is a process that comes with challenges. The redevelopment of brownfield sites is complex and typically involves several stakeholders who must collaborate to achieve sustainable development (CABERNET, 2006; Hammond et al., 2023a; Limasset et al., 2017). Making strategic decisions around land use redevelopment requires consideration of many different factors addressed in a structured manner to allow the best-possible decision to be undertaken (Loures and Vaz, 2018). The interaction between environmental constraints, social factors, economic consideration and often conflicting stakeholder preferences creates barriers (i.e. differing expectations for site end-use) that must be overcome to realise the opportunities presented by the redevelopment (Hammond et al., 2023b). Balancing these factors can make decision-making for sustainable land development a challenging process. To achieve planning and development goals using evidence-based decision-making, it is crucial to utilise methods that supplement subjective judgment (Crook et al., 2019).

Informative digital tools can support stakeholders in the decision-making process pertaining to redeveloping brownfield land (Alexandrescu et al., 2017; Bartke et al., 2016; Hammond et al., 2021). Over the past few decades numerous digital tools have been developed to aid those stakeholders involved in brownfield decision-making (Huysegoms and Cappuyns, 2017) including the development of Decision Support Systems (DSSs). DSSs are specialised digital tools that are structured in a way that enhances the value of data and information and improve a decision-makers understanding of an issue or problem, often through decision analysis or spatial visualisation of the data. DSSs fall between two classifications of functionality: (1) information-based, which present information and may include some data analysis; and (2) model-based, which typically incorporate a problem-solving element such as numerical decision analysis (Black and Stockton, 2009; Hammond et al., 2021; Marcomini et al., 2009). In the context of brownfield development, DSSs can be used by planners, developers, contractors, and their advisors to improve decision-making processes (Cappai et al., 2019). One commonly used decision analysis technique in brownfield DSSs is Multi-Criteria Decision Analysis (MCDA), which is often used to rank and/or select the most suitable contamination remediation (clean-up) methodology for a particular site (Huysegoms and Cappuyns, 2017; Sorvari and Seppälä, 2010; Stezar et al., 2013). Key brownfield DSS tools include DESYRE DSS (Carlon et al., 2008; Critto and Agostini, 2009; Pizzol et al., 2009), SADA DSS (Purucker et al., 2009), SCORE DSS (Rosén et al., 2013, 2015; Söderqvist et al., 2015), TIMBRE (Pizzol et al., 2016) and, SYRIADE (Agostini et al., 2012; Pizzol et al., 2011; Zabeo et al., 2011). A critical review of brownfield DSSs developed between 1998 and 2021 was conducted by Hammond et al. (2021), highlighting key studies, trends in existing research, and areas for potential improvement. The review highlighted that the focus of existing research on DSSs for brownfield development centred on: (1) selecting a suitable remediation methodology for a site; and (2) assessing land use suitability. A smaller number of studies were reported as focussing on other applications, such as modelling groundwater contamination risk or estimating remediation costs for sites. Although numerous DSS have been developed and successful case studies have been demonstrated, the regular use, uptake and implementation of DSSs into the day-to-day operations of brownfield redevelopment stakeholders remains low (Ameller et al., 2020; Hammond et al., 2021). Reasons for this have been discussed by Hammond et al. (2021) where several limitations of existing brownfield DSS research are reported.

The aim of this paper is to develop a novel methodology and outputs for a DSS that can aid in the early-stage planning and redevelopment of brownfield sites at a city-region scale.

2. Methods

The methodology used to create and evaluate the DSS follows a series of steps as follows; (1) the rationale for the DSS and scope of application, created through direct stakeholder engagement (section 2.1); (2) a high-level summary of the digital architecture of the DSS and its modules (section 2.2), (3) the methods used to create the outputs contained within the DSS modules and the DSS user interface (section 2.3 to 2.6) and, (4) methods used for user testing (section 2.7).

The DSS was informed by end-user insights from the Liverpool City Region Combined Authority (LCRCA). The Liverpool city region was used as a case-study area to demonstrate the application and functionality of the DSS for purposes of user testing and evaluation. LCRCA is a mayoral devolved administration in north-west England responsible for six local authorities (Liverpool, Sefton, Knowsley, Halton, St. Helens, and Wirral) covering an area of 723 km^2.

The DSS was applied and tested using three distinct areas within LCRCA; (1) 31,942 ha of post-industrial land, (2) 2783 brownfield sites (6185.3 ha) identified during a strategic land assessment, and (3) 16 future housing sites (1159 ha) and 8 future employment sites (1033 ha) identified from local plan policy areas within St Helens. The size and distribution of the brownfield sites assessed vary greatly, with many small sites located in urban and inner-city Liverpool, while larger and less numerous sites can be found in peri-urban and rural areas in Knowsley, Sefton, and St. Helens (Hammond et al., 2023a).

The methods presented in this paper describe the procedure used to create the DSS outputs. The results describe the general functionality of the DSS for intended use cases, and present results from user testing carried out to evaluate and improve the DSS. Full details of the case-study application to the Liverpool City Region and verification of DSS outputs are reported in Hammond et al. (2023a).

2.1. DSS scope

The need to develop a novel DSS framework to support early-stage brownfield planning and redevelopment at a city-region scale was informed by previous research and stakeholder engagement (Hammond et al., 2023b). The development approach for DSS should be; stakeholder-driven, problem-centred, visual, intuitive, interactive, interoperable, and geospatial data-driven (Hammond et al., 2023b). The DSS produced and reported here is a live-data prototype WebGIS application that includes three modules for the assessment of land use potential, risk assessment of ground conditions, and economic viability assessment. The DSS was designed with direct involvement from stakeholders to optimise user-friendliness and align it with their needs. The aim of the DSS is to encourage sustainable, early-stage, land use planning and resource allocation by considering environmental, social, and economic factors simultaneously.

To inform the design of the DSS and outputs, a use case was created through detailed semi-structured discussions with intended end-user stakeholders. This use case consists of three steps: (1) problem statements specific to the sector, (2) user personas and identifying users and their unique characteristics, and (3) engaging with users to develop user stories to describe how their decision-making process aligns with the DSS.

Based on previous work and studies (Hammond et al., 2021, 2023a, b), five problem statements were defined, as follows:

1. Difficulty in accessing and understanding spatial data for brownfield redevelopment, hindering knowledge exchange between experts and non-expert stakeholders.
2. Varied GIS capabilities within local/regional governments, with some stakeholders having difficulty utilizing spatial datasets in decision-making.
3. Lack of digital tools to support early-stage land use planning and decision-making in existing DSSs.

4. Existing DSSs overlook social and economic dimensions of brownfield decision making, with a predominant focus on environmental and contamination issues, such as remediation technology selection.

5. Existing DSSs use non-intuitive interfaces and lack stakeholder-led design, making them challenging to use and apply to real-world problems.

Finally, to maximise the likelihood that the DSS is useful and user-friendly, it was found important to establish a clear understanding of the intended users and their operations. Therefore, three stakeholder groups from the city region government, LCRCA, who could benefit from the DSS were engaged in the research. Through semi-structured discussions with these stakeholders, three 'user personas' were created (Fig. 1), which provide information on their roles, goals, operational challenges, and current digital capabilities and workflows. Further semi-structured discussion with these stakeholders allowed for the synthesis of 'user stories' where theme-specific challenges are identified (Table 1).

2.2. Overview of the DSS modules

The DSS has three modules and a summary screen created using ESRI's ArcGIS pro and ArcGIS Online suite of tools (ESRI, 2023). The summary screen combines selected outputs from each module to provide a comprehensive view for users to assess their sites. Users can select sites through the WebMap or a list, and the data-dashboard-like interface returns key data which can be exported for subsequent external use. A summary of methodology and geoprocessing steps taken to transform, process, and integrate data for the DSS is presented in Fig. 2. The DSS modules comprise the following:

Module 1 scores Land Use Potential for five end-uses (Residential, Small-Commercial, Large-Commercial, Greenspace, and Mixed-Use) through interactive GIS layers within WebGIS maps, helping users explore Land Use Potential and support decision-making. The criteria shown in Table 1 refers to factors that determine Land Use Potential,

weighting reflects their degree of influence, and attribute score is a numeric value (0–1) used in the MCDA calculation.

Module 2 provides estimates of ground risk presented as interactive GIS layers within WebGIS maps, allowing users to investigate potential issues around ground risk for areas of interest. The ground risk scores are taken from the Groundscreen data product created by Groundsure (2023). Further details of the methodology are provided in section 2.4.

Module 3 presents a series of datasets that provide evidence for economic viability assessments, comprising estimated remediation costs, land value, and total new build property sale price. Users can interact with these data to assess the financial viability of an area, individual site, or portfolio of sites, following identification of areas of interest during initial screening of land use potential ground risk.

The DSS generates results for two spatially explicit areas, (1) User defined sites, and (2) an area of Post-Industrial Land. User defined sites are those areas that are drawn on-screen or uploaded by the user when using the DSS, for the purpose of prototyping a portfolio of brownfield sites and future development areas were used as 'user defined sites' (section 2). Post-Industrial Land (PIL) was generated in GIS using historical land use data to identify previously developed land.

2.3. Module 1 - land use potential

The Land Use Potential layer employs GIS-MCDA, which defines multiple criteria, being specific factors affecting Land Use Potential for each end use. These factors are weighted by their considered 'degree of influence' (1–10), and specifics of criteria (i.e. walkability zones, or zones of suitability around features represented by the criteria) as defined within attributes used in GIS-MCDA calculations. Output data layers include ten Land Use Potential maps for residential, small-scale commercial, large-scale commercial, greenspace, and mixed-use, each visualised for user defined sites and post-industrial land areas. Fig. 3 provides an overview of the approach used to create the Land Use Potential outputs for the DSS.
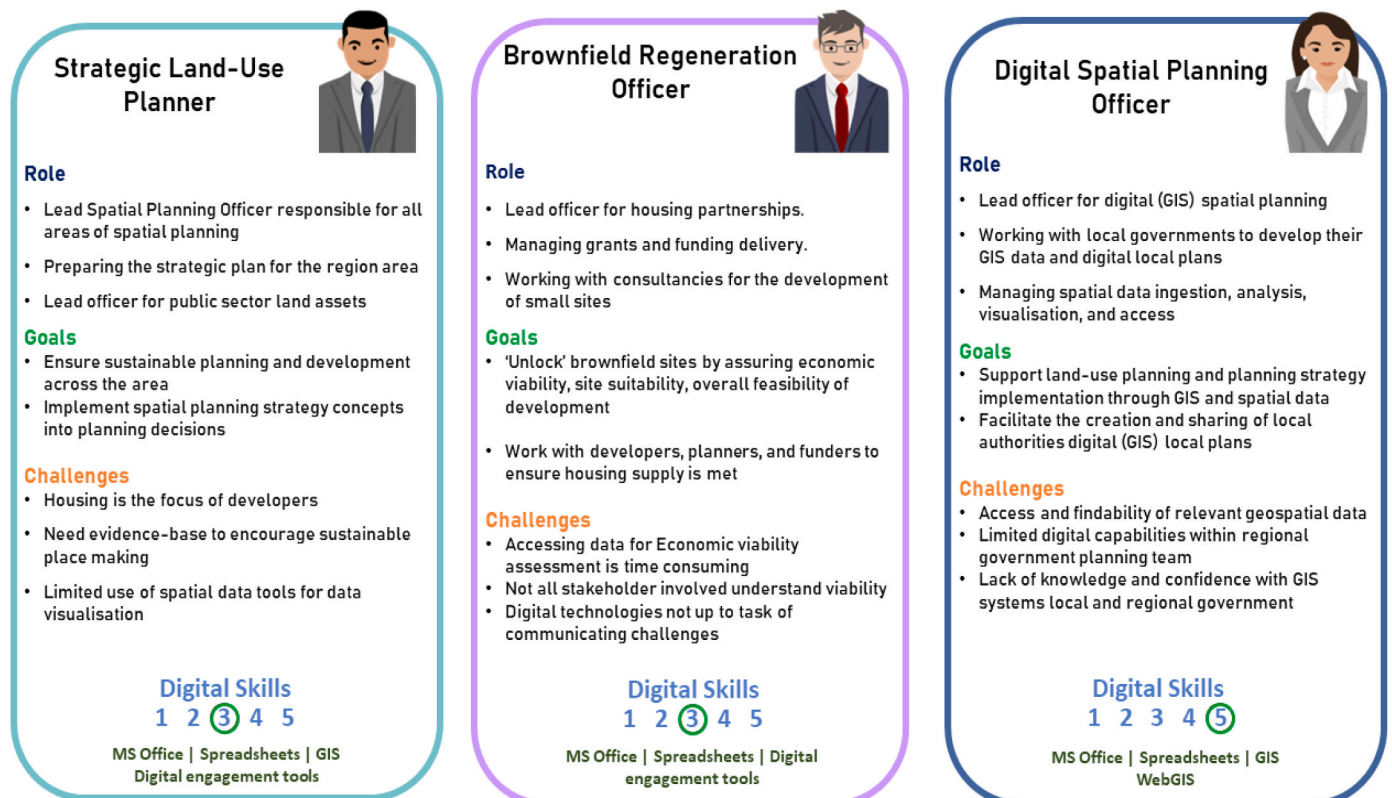

Fig. 1. User personas for the DSS use-case, digital skills range from 1 (least skilled) to 5 (highly skilled).

Table 1
User stories.

| Theme	User	Description
Land Use Potential	Strategic Land Use Planner	Decision-makers find it challenging to plan for brownfield sites, with developers typically favouring housing developments. To ensure sustainable place-making, it is crucial for regional government to promote alternative end-uses such as public open space.
Economic Viability	Strategic Land Use Planner, Brownfield Regeneration Officer	Economic viability is a major issue in brownfield redevelopment, with data analysis being difficult and non-expert stakeholders lacking understanding of viability. Accessing and understanding data related to viability assessment is crucial for project success.
Ground Conditions	Brownfield Regeneration Officer	Brownfield sites often have problematic ground conditions that pose risks and cost implications for development. Understanding these implications early-on is essential for project success.
Digital Capabilities	Strategic Land Use Planner, Digital Spatial Planning Officer	The varying digital capabilities among regional and local governments call for an intuitive and easy-to-use solution that can be utilized and understood by stakeholders with different levels of digital abilities.
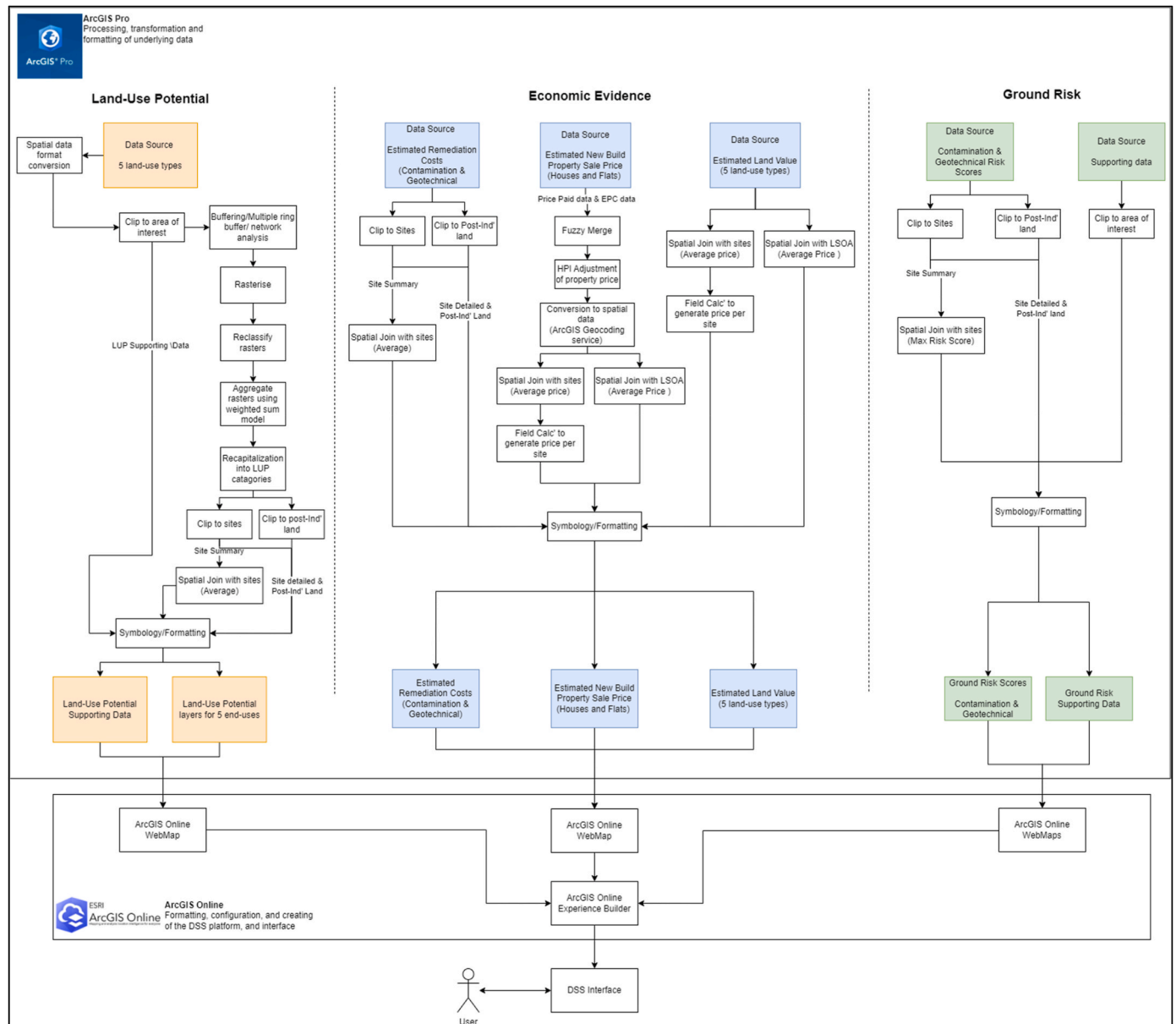
Fig. 2. Summary of geoprocessing steps taken to transform, process, and integrate data for the three DSS modules.

To create Land Use Potential layers, criteria were selected based on input from stakeholders and a literature review. The final list of criteria is presented in Table 2, where each criterion is mapped to a corresponding Land Use Potential category. The stakeholder engagement process involved a one-day workshop and a follow-on two-day user testing workshop to identify land use planning criteria through facilitated group discussion. The literature review focused on land use planning decision support systems and relevant grey literature, such as the National Design Guide 2021 (DLUHC 2021), and the National Planning Policy Framework 2021 (MHCLG 2021). For the complete list
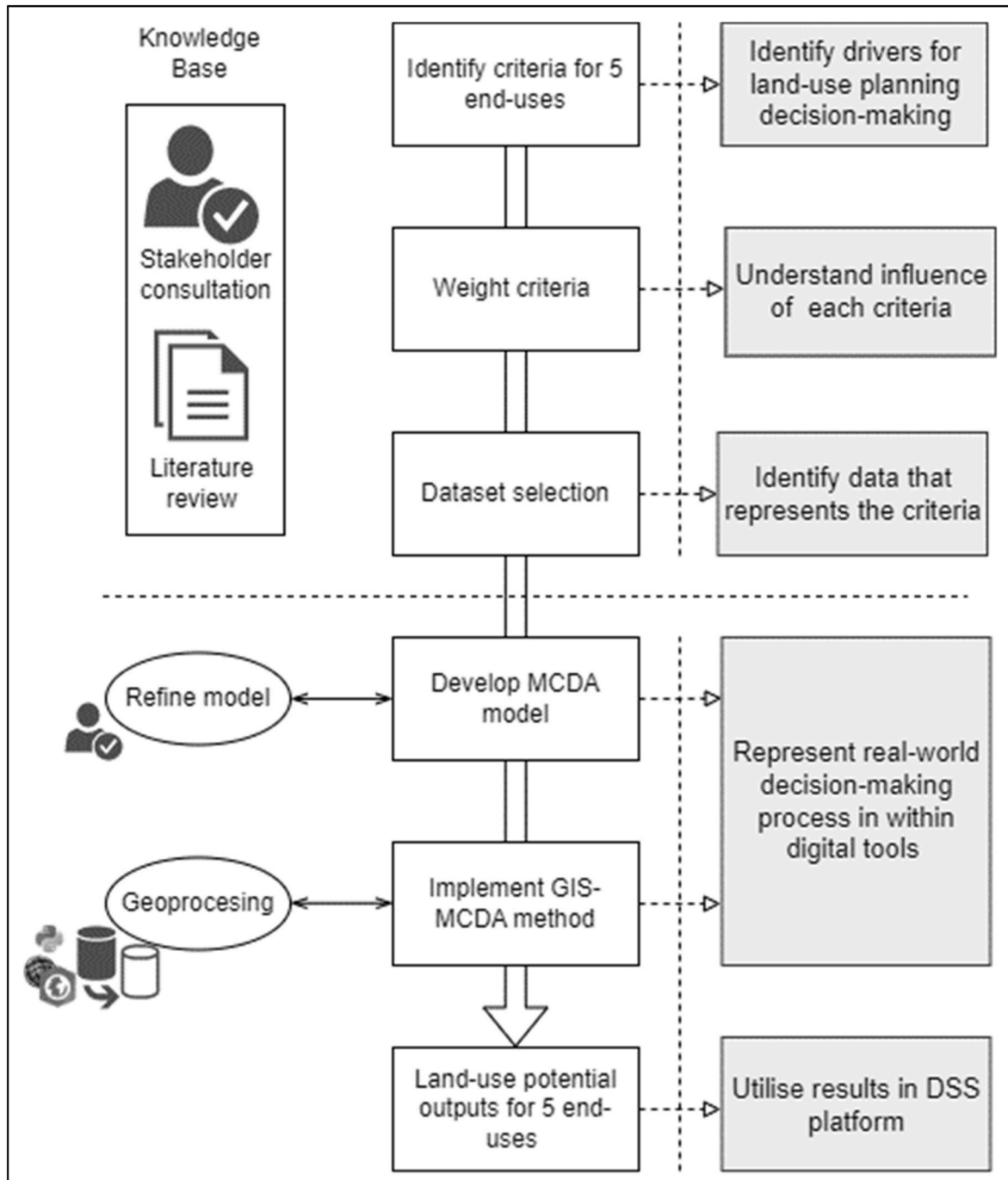
Fig. 3. Overview of methodology approach for Land Use Potential outputs.

of chosen criteria with justification refer to the supplementary material (S1 – Sheet 1).

To ensure the weightings were representative of the priorities and opinions of decision-makers, findings of criteria review were shared with stakeholders for feedback. A list of criteria was distributed to stakeholders asking them to score each from 1 to 10 based on its influence on a specific end-use, with 1 being low influence and 10 being high influence. A weighting for each criterion was calculated by taking the average of the stakeholder scores. An MCDA for each land use potential end-use model was developed in a spreadsheet using the criteria and weights for each dataset. This model identifies the optimal planning scenario for each end-use, where the maximum score indicates an ideal site.

Creating a geospatial model for Land Use Potential involved representing each criterion with a geospatial dataset layer. While some criteria, such as Flood Risk Zones and demographic data, were readily available from external sources, others required specific geoprocessing steps. For instance, the locations strategic logistic hubs were digitized to calculate *distance to market*. For a full list of datasets used refer to the supplementary material (S1 - Sheet 2).

The MCDA model is based on the *weighted sum model* (WSM) (Fishburn, 1967) and is constructed as follows:

Equation 1:

$$A_i^{Score} = \sum_{j=1}^{n} w_j a_{ij}, for\ i = 1, 2, 3, \ldots$$

Table 2
Land Use Potential criteria selected, including weightings (1 – Low influence, 10 – High influence).

Land use Type	Criteria	Weighting (1–10)	Criteria Score
Residential	Proximity to health infrastructure	7	400m - 1 800m - 0.66 1200m - 0.33
	Proximity to active travel routes	9	400m - 1 800m - 0.66 1200m - 0.33
	Proximity to public transport	9	400m - 1 800m - 0.66 1200m −0.33
	Proximity to major roads	9	1600m - 1 >1600m - 0.5
	Proximity to town centres	8	400m - 1 800m - 0.66 1200m −0.33
	Proximity to existing shops (food)	8	400m - 1 800m - 0.66 1200m −0.33
	Proximity to community venues	7	400m - 1 800m - 0.66 1200m −0.33
	Proximity to green spaces	8	400m - 1 800m - 0.66 1200m −0.33
	Proximity to education establishments	9	400m - 1 800m - 0.66 1200m −0.33
	Proximity to cultural sites	6	400m - 1 800m - 0.66 1200m −0.33
	Within greenbelt area*	N/A	N/A
	Population density	7	Class 10 - 1 Class 9 - 0.9 … Class 2 - 0.2 Class 1 - 0.1
	Flood risk zone 1 & 2	7	Zone 1–1 Zone 2–0.5
	Flood risk zone 3[a]	N/A	N/A
	Proximity to sites of natural value	7	N - 1 Y - 0.5
Large-Scale Commercial	Proximity to motorway links	9	1600m - 1 2500m - 0.66 3200m - 0.33
	Distance from residential areas	7	250m - 0.2 500m - 0.4 750m - 0.6 1000m - 0.8 1250m - 1 1500m
	Size of site (critical criteria)[a]	N/A	N/A
	Distance to market	8	2500m - 1 5000m - 0.66 7500m - 0.33
	Proximity to rail access	8	2500m - 1 3000m - 0.66

Table 2 (*continued*)

Land use Type	Criteria	Weighting (1–10)	Criteria Score
			3500m - 0.33
	Proximity to public transport	8	400m - 1 800m - 0.66 1200m −0.33
	Proximity to active travel routes	8	400m - 1 800m - 0.66 1200m −0.33
	Proximity to major roads	9	200m - 1 300m - 0.75 400m - 0.50 500m - 0.25
Small-Scale Commercial	Proximity to public transport	10	400m - 1 800m - 0.66 1200m −0.33
	Proximity to active travel routes	9	400m - 1 800m - 0.66 1200m −0.33
	Proximity to town centres	8	400m - 1 800m - 0.66 1200m −0.33
	Proximity to residential areas	8	400m - 1 800m - 0.66 1200m −0.33
	Deprivation score	8	Class 10 - 1 Class 9 - 0.9 … Class 2 - 0.2 Class 1 - 0.1
Greenspace	Proximity to another greenspace	8	100m - 1 200m - 0.8 300m - 0.6 400m - 0.4 500m - 0.2
	Proximity to schools	8	400m - 1 800m - 0.66 1200m −0.33
	Proximity to residential areas	8	400m - 1 800m - 0.66 1200m −0.33
	Sustainable transport (active travel)	9	400m - 1 800m - 0.66 1200m −0.33
	Flood Risk Zone	8	Zone 3 - 1 Zone 2 - 0.66 Zone 1 - 0.33
	Proximity to major roads	8	1600m - 1 >1600m - 0.5
	Deprivation score	8	Class 10 - 1 Class 9 - 0.9 … Class 2 - 0.2 Class 1 - 0.1
	Public Health improvement area	7	Class 10 - 1 Class 9 - 0.9 … Class 2 - 0.2 Class 1 - 0.1
	Proximity to sites of natural value	3	<100m - 1 >100m- 0.5

[a] **Critical Criteria**.

where n are the decision criteria, w_j denotes the relative weight of importance of the criterion, a_{ij} is the performance value (criteria score) of each grid cell A_i when it is evaluated in terms of the criterion, and the total score for each grid cell is denoted as A_i^{Score}. Following this each grid cell score was adjusted to generate a final Land Use Potential Score between 0 and 1, where 1 indicates the ideal result, as follows:

Equation 2:

$$\text{Land Use Potential Score} = A_i^{Score} \div max\left(\{A_i^{Score}, \ldots A_n^{Score}\}\right)$$

Geoprocessing was performed using ArcGIS Pro and Python scripts to create Land Use Potential layers. When data were provided in a non-interoperable format, it was converted using data conversion and interoperability tools within ArcGIS Pro Spatial data were clipped to the study region and then buffered, rasterised, reclassified, or subjected to network analysis, using OpenStreetMap road/path layers, to create areas scored for Land Use Potential. Specifics of transformation applied to individual criteria-datasets can be found in the supplementary material (S1 – Sheet 1). The raster layers were created using a pre-generated empty raster dataset of the study area and were then reclassified, and aggregated by implementing the weighted sum model aggregator within the suitability modelling workflow within ArcGIS Pro.

The final score for each cell was set to range from 0 to 1, then categorized into user-friendly classes. (Table 3). Selected source data attributes were preserved and presented in their respective final LUP layers.

To identify mixed-use sites, the residential, greenspace, and small-scale commercial potential layers were added and divided by three using the raster calculator tool in ArcGIS Pro.

The resulting score ranges from 0 to 1 and were assigned to classes (Table 2). The resulting maps was converted to polygons using the 'to feature tool' and dissolved to create polygons Land Use Potential and. clipped to the Post-Industrial Land area.

The mean suitable score from all intersecting raster cells was joined with the case-study site polygons using the spatial join function. Critical 'no development' criteria (Table 2) were applied for residential and large-scale commercial potential layers, which include flood risk zone 3 & greenbelt land, and a minimum site size of 4 ha, respectively. Sites that met the critical 'no development' criteria these criteria were then manually re-scored as 'Development not advised'. All LUP layers were organized into ArcGIS Pro map projects for each land use category, with the layers grouped into whole area and site summary, and the symbology and attribute field names defined. Once completed, the Land Use Potential layers were uploaded to ArcGIS Online using the built-in tools in ArcGIS Pro and uploaded as WebMaps for integration into the ArcGIS Experience Builder DSS Interface.

2.4. Module 2 - ground risk

Ground risk data (Groundscreen) were shared with the authors by Groundsure as a Geopackage (.gpkg) database and then converted to ESRI File Geodatabase using conversions tools in QGIS for use in ArcGIS Pro. The data for a given area are presented by a 0.25 ha hex-grid layer that is attributed with a risk score for each category (contamination or geotechnical). The Groundscreen methodology is unable to be described in full here due to commercial constraints but is based GIS-MCDA methodology that integrates environmental and geological spatial data

Table 3
Land Use Potential categories.

Land Use Potential Score	Land Use Potential Classification
0.80–1	Very High Potential
0.60–0.79	High Potential
0.40–0.59	Medium Potential
0.20–0.39	Low Potential
0.00–0.19	Very Low Potential

to produce ground risk scores for contamination and geotechnical hazards, based upon the source, pathway receptor (S–P–R) model. For example, for sources of contamination, datasets such as *Recorded Pollution Incidents* and *Historical Landfills* (Environmental Agency) were used, for pathways, datasets such as *Boreholes* (British Geological Survey) and *Mine Entries* (The Coal Authority) were used, for receptors, datasets such as *Groundwater Vulnerability* (Environmental Agency) and *Surface Water Features* (Ordnance Survey) were used. The WSM was used to generate a score for each S-P-R component and then integrated as follows:

Ground Risk Score = Normalised Sum of Source Scores *x* Normalised sum of pathway and receptor scores.

Using the Batch Clip function in ArcGIS Pro, the supporting data layers were clipped to the area of interest (in this case the Liverpool City Region area). The layers were then grouped into themes (Contamination and Geotechnical) and their symbology and attribute field names were defined in an ArcGIS Pro map window. The resulting ArcGIS Map output was published to ESRI's ArcGIS Online using the built-in upload tools. For the ground risk scores, the data was first clipped to the case-study sites using the Clip function in ArcGIS Pro. Then, the dataset was duplicated to represent both dimensions of ground risk (contamination and ground instability) as two distinct layers.

The ground risk maps were clipped to the area of post-industrial land using the Clip function in ArcGIS Pro, resulting in a ground risk map for post-industrial land. The Groundscreen data were then joined to the case-study sites using the spatial join function in ArcGIS Pro, with a maximum value of ground risk for the summary field to provide the worst-case scenario for ground risk. This was undertaken twice to produce two site summary ground risk datasets for both contamination and ground instability, respectively. The resulting layers were configured in individual ArcGIS Pro map windows, with separate projects for each dimension of ground risk. The layers were then grouped into themes and their symbology and attribute field names were defined. Finally, the ArcGIS Map containing the Ground Risk data was uploaded to ArcGIS Online using the built-in upload tools.

2.5. Module 3 - economic evidence

2.5.1. Remediation costs

Within the Groundscreen data product, there are specific fields that are to be used for estimating contamination and geotechnical remediation cost. Within the Groundscreen data product, contamination and geotechnical remediation costs were included per hex grid cell. Groundscreen data were again converted to ESRI File Geodatabase format using conversions tools in QGIS.

Using ArcGIS Pro's Clip function, the dataset was clipped to the case-study sites and post-industrial land area. Two layers were created to represent the two dimensions of ground risk which are contamination and ground instability. The contamination remediation cost estimate was calculated using the Groundscreen methodology, which involved using the field calculator to generate upper and lower scores for three different development scenarios (Residential, Public Open Space, and Commercial Development). This methodology is based on a report covering estimating remediation costs (Homes & Communities Agency, 2015). The cost estimation values were then joined to the case-study sites using the spatial join function, and two site summary cost datasets produced for contamination and ground instability.

2.5.2. Estimated new build property sale price

The Estimated New Build Property Sale Price data theme consists of six datasets created for this project (Supplementary material - S2). These datasets include estimated new build house and flat total sale prices per site, as well as average house and flat prices by Lower Super Output Area (LSOA) for post-industrial land, both per m^2 and overall. To create these datasets, publicly available Price Paid data and House Price Index data from HM Land Registry, along with Energy Performance Certificate data

from the Department for Levelling Up, Housing & Communities, were merged using a methodology developed by Three Dragons Ltd (Three Dragons, 2023). The data were downloaded in CSV format for the area of interest and processed using Excel. A fuzzy-merge method was used to match the Price Paid and EPC data, due to inconsistencies in spelling, formatting, and input errors. The fuzzy-lookup add-in for Excel was used to match similar rows based on address. This process was implemented separately for houses and flats.

The full methodology for Estimated Property Sale price data and Land Value Estimates data is available in the supplementary material (S2). The economic evidence layers were configured and uploaded to ArcGIS Online as described for the other modules (section 2.4 and 2.5).

2.6. User interface

The user interface was developed within the ArcGIS Online Experience Builder (EB) Platform (ESRI, 2023). The DSS user interface was created using a two-stage process: (1) a wireframe mock-up was created to establish the visual details of the interface, which was used to create (2) an alpha version of the DSS. Feedback from stakeholders and the project team was used to improve the DSS, resulting in the beta version. User testing was conducted on the beta version, which was used to further improve the interface. Pages were created in the EB platform to match the wireframe mock-up, and ArcGIS Online WebMaps were configured accordingly. Experience Builder was chosen due to its customizability and ability to fit into existing ESRI GIS workflows.

2.7. User testing

User testing of the DSS was conducted with stakeholders from the Liverpool City Region Combined Authority. The testing was conducted through a workshop consisting of four sessions held over two days with 15 stakeholders involved, each with different roles and levels of experience (Supplementary Material, S1 – Sheet 4). During each session, stakeholders interacted with the DSS and were asked to carry out several site assessment tasks to test its functionality. Comments were recorded and participants were asked to complete a feedback form at the end of

each session. The feedback forms consisted of three parts: (1) profiling questions, (2) a table to score five usability aspects of the DSS, and (3) ten questions on strengths, weaknesses, and the applicability of the DSS to their role. All feedback gathered in this way was compiled and analysed to provide insights on DSS usability and ability to support decision-making. Based on the feedback, improvements were implemented on the DSS, and future development needs and improvements recorded.

3. Results

3.1. Decision support system

The user journey through the DSS was intentionally designed to provide stakeholders with a quick overview of sites before delving into the details of each module (Supplementary Material, Fig. S5.1). The user journey was created with input from the project team and case-study stakeholders during the wireframe and early prototype stages and was further refined based on feedback from user testing (Section 4).

The general layout and functionality of the DSS interface are consistent across the three modules (Fig. 4). The module navigation bar allows users to move between the three modules, preserving the previous settings. Similarly, in-module navigation buttons allow users to load the different layers/models present within that module, for example, moving between the different Land Use Potential types within the Land Use Potential module. The DSS includes filtering tools, allowing the user to constrain the presented datasets based on a user-defined selection/range.

The principal data visualisation in the DSS takes place within the map window, where users are able to use their mouse or touchscreen to zoom, pan, and interact with the spatial data presented in the map window. Interaction with the data triggers a customised pop-up with details of data/DSS outputs for that site and/or area. Within the DSS interface a legend is present on the left of the screen, allowing the user to interpret the symbology for spatial data outputs within the map window. Finally, layer controls allow the user to toggle visibility of spatial data layers (Post-Industrial Land, Site Summary, Site Detailed), as required. A basemap toggle allows users to change the basemap of the map window
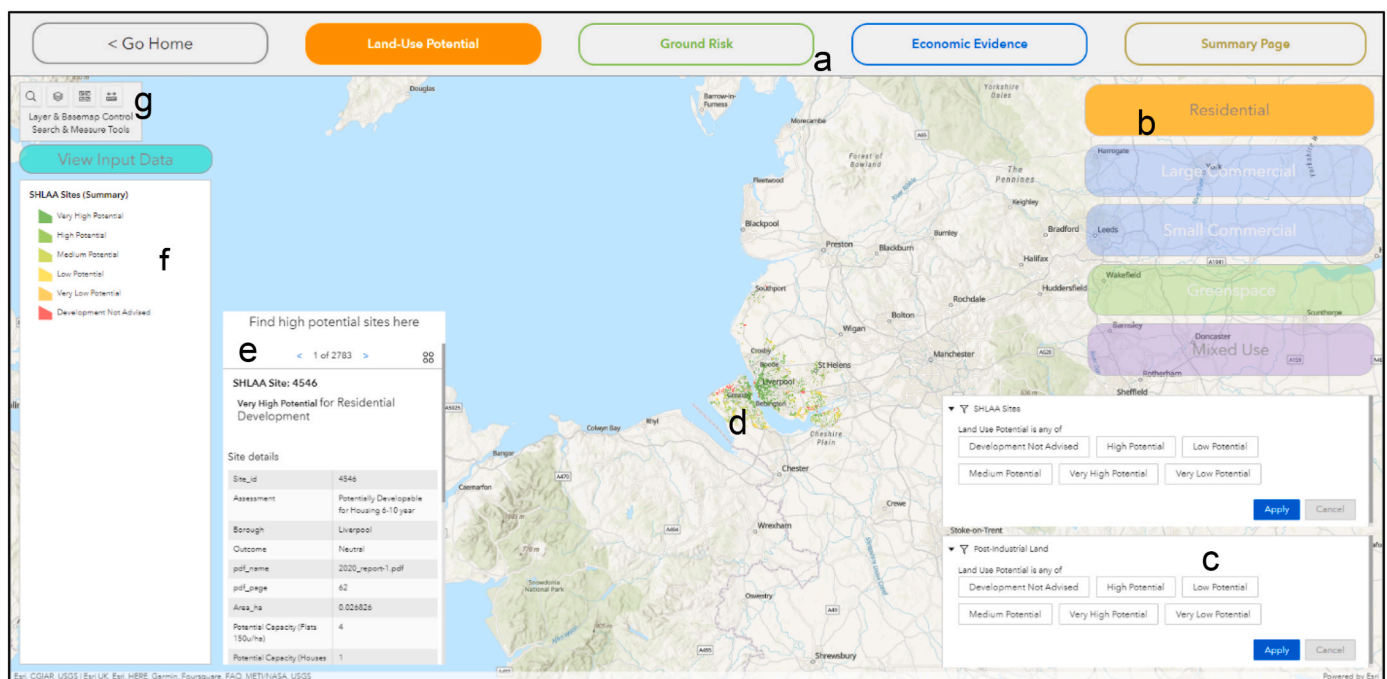

Fig. 4. The user interface of the DSS, showing elements of general functionality are highlighted: Module navigation bar (a); In-Module navigation (b); Filtering tools (c); Map window (d); Summary tool (e); Legend (f); Layer control, basemap toggle, search, and measuring tools (g).

(i.e., satellite view vs topographic mapping), and the search tool allows the use to find any location of interest using the ArcGIS World Geocoding Service.

3.1.1. Reviewing high-level deliverability of sites

Whilst each module of the DSS allows users to investigate a different dimension of brownfield land use planning and development, when combined the DSS, datasets presented within it and functionality allows for rapid, high-level assessment of a multi-scale issues. This includes using each module individually, to challenge assumptions of planning applications, or evidencing planning/funding decisions, but also assessing large areas simultaneously for early-stage deliverability assessment. To support this functionality within the summary screen (Fig. 6) allows users to select a site, or range of sites and returns the key classifications, scores, and values form the three modules. Additional functionality within the summary screen page includes filtering tool, context layers and others, to assist users in identifying sites/areas for investigation/comparison. For example, a developer may have submitted an initial planning application for two neighbouring sites for residential development (Fig. 5). Using the summary screen, the planning officer is able to quickly load, high-level information to sense-check some of the assumptions of ground risk, economics, and suitability/potential for housing.

3.1.2. Assessing a site or area potential for different end-uses

Within the Land Use Potential module of the DSS, there are multiple elements of functionality designed to support the user's ability to conduct land use planning activities. The three types of Land Use Potential layers within the DSS support different scales of investigation. The post-industrial land (Supplementary Material, Fig. S5.2) and Site Summary (Fig. 5a) LUP layers, assist with carrying out high-level identification/comparison of many sites/areas for certain types of land use.

The Site Detailed layer (Fig. 5b) allows for an intra-site assessment of Land Use Potential on a 50 m resolution. This allows users to identify areas of a sites, particularly large sites, where different types of land use may be more suitable, helping to inform site layout. The Site Detailed Layer is supported by filtering tools, assisting the user with identify sites of areas of large sites that match their search criteria, helping to include/exclude sites/areas from their assessments.

Users are able to load a wide variety of other layers alongside the Land Use Potential layers. These could be the in-built contextual layers (chosen by land use planners during stakeholder consultation phase to contextualise land use planning data) and includes areas of deprivation, existing areas of development, and multiple political boundaries. As shown by Fig. 5c, pop-ups are configured in a way that presented users with the crucial information for Land Use Potential, including the underlying drivers for a particular Land Use Potential classification. Users then open the input data window to visualise the underlying datasets allowing them to better understand and investigate that Land Use Potential classification. For example, in Fig. S5.2 (Supplementary Material), residential development for post-industrial land is being visualised alongside areas of deprivation to help identify high-priority development areas for housing as part of an exploratory spatial planning scenario.

3.1.3. Investigating ground risk of a site

The Ground Risk module allows users to interpret and understand the potential ground risk posed to a site/area by contamination and geotechnical hazards (Supplementary Material, Fig. S5.3). Post-industrial land and site summary allowing for high-level assessment, whereas site detailed allowing for intra-site identification of areas of higher risk. The site detailed view (Supplementary Material, Fig. S5.3) aides land use planning stakeholders, as well as land developers and consultants in querying site development plans and the design of ground investigation activities to target areas of higher risk.

If a user seeks to investigate the underlying reasons a ground risk score, they are able to open the supporting data window (Supplementary Material, Fig. S5.4), where they are able to load all of the input data and analyse it through detailed pop-ups.

For example, Fig. S5.4 shows historical land use data which when clicked on shows that this area was recorded to be an Oil Depot in 1975, placing it at an increased likelihood of contamination hazards being present on the site.
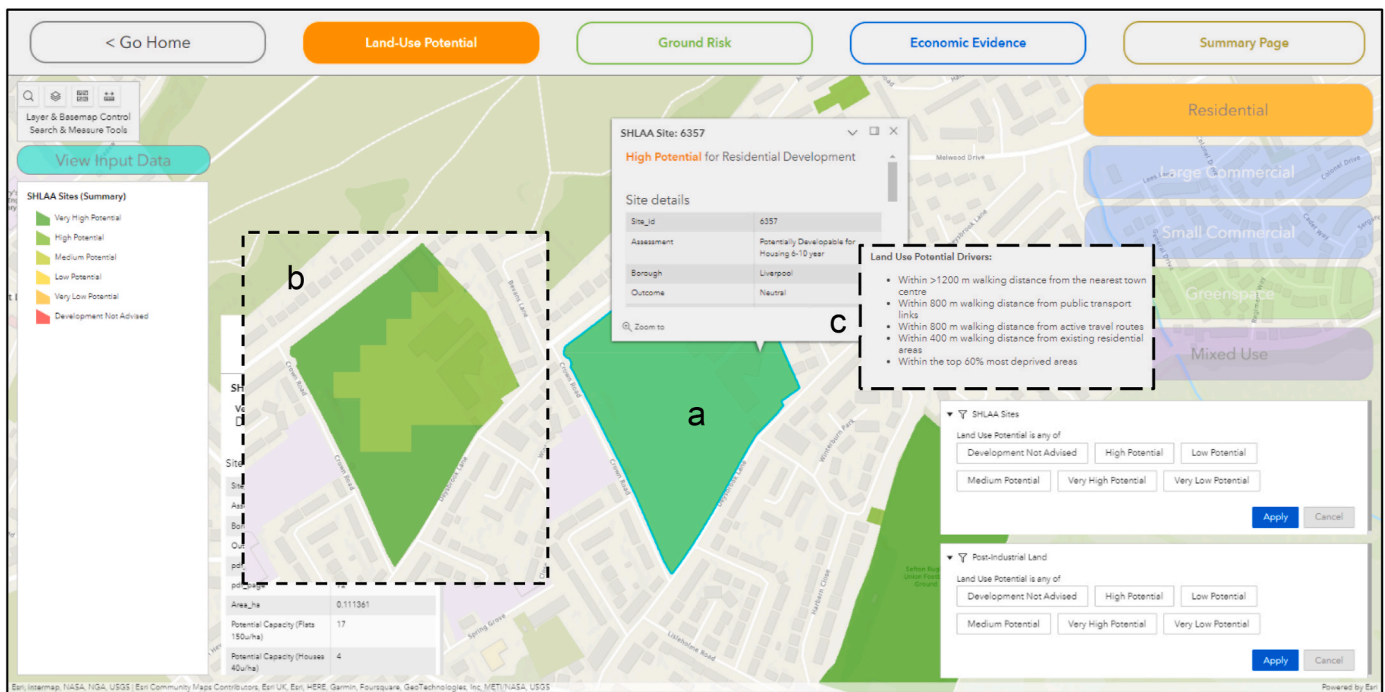

Fig. 5. The user interface of the DSS for Land Use Potential Module showing an example of the site summary view (a), the Site detailed view (b), and Land Use Potential drivers within the pop-up window (c).
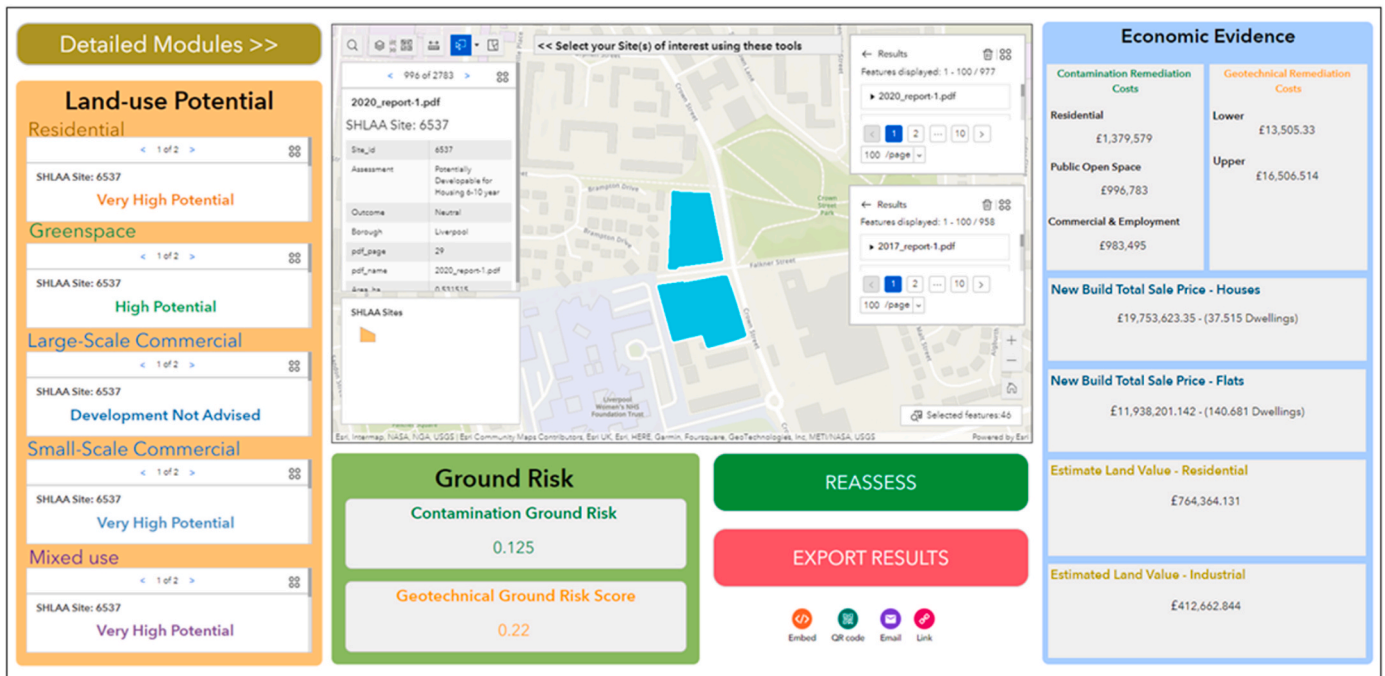
Fig. 6. The user interface of the DSS for the summary screen.

In-map summary tools (Fig. S5.3) within the ground risk module have been configured to show the highest risk sites. This supports land use planners, and other stakeholder in identification of sites within a portfolio where the most special intervention/funding/investigation may be needed to address abnormal around conditions. Also present in the ground risk module is a link to guidance on dealing with contaminated land (Supplementary Material, Fig. S5.3).

3.2. User testing results and feedback

The user testing participants used the DSS to carry out an initial investigation of 12 sites in and around Liverpool. For each site, the participants identified the Land Use Potential, ground risk and assess potential economic constraints. Participants used the DSS to find, understand, and extract the information required for each scenario. Participant comments (Supplementary Material, S1 – Sheet 4) indicated positive attitudes the overall usefulness of the DSS and its potential to help them and their teams with comments like "Really useful and detailed tool … [the DSS would be] extremely adaptable to our work" – *Combined Authority Planning Officer*. Overall, the DSS was well received with most of the stakeholders giving positive comments on useability, relevance to their role, and the degree to which the DSS and its outputs would help them make better decisions in their roles.

Figure S5.5 (Supplementary Material) illustrates the usability results of the DSS. The radar plots demonstrate that the DSS received high overall usability evaluations from users, with slight variations among different stakeholder types. These findings suggest that the DSS has effectively met the usability requirements of its target user base. The biggest difference between participant responses is DSS Layout/Flow where scores for the DSS Layout/Flow were on average between 2 and 3. However, comments around this aspect of the score were analysed further. This showed that users attributed this to technical difficulties experience with the internet connection at the workshop disrupting the *flow* of the analysis they were carrying out, rather than any specific functionality of the DSS.

Key points established following the user feedback include:

- Land Use Potential module was deemed by most users to be accurate to their understanding of the site's potential. Most users commented that this module is most useful when combined with their own knowledge of a site area, feeding into their assessments.
- The Ground Risk module was also deemed to be accurate according to users' experience and understanding for sites they were familiar with, most of them commented that it was a "good module to gain good understanding of what underlying risks are for sites, and that the supporting was extremely helpful too to help justify planning decisions etc."
- Most users commented that economic evidence data was accurate according to their understanding, but that some more ground truthing and adjustment of densities for sale price data would help to improve accuracy. One particularly apt quote was that it was: "Detailed enough to make reasonable and well evidence decision as part of an early assessment" – *Local Authority Planning Officer*.
- 13 out of 15 users said they would be either likely or extremely likely to use the tool in their role. When asked how they would use the DSS, a range of application was given, mostly centred around assessing planning applications, and providing an evidence base for strategic planning.
- All 15 users either Agreed or Strongly Agreed, that the DSS would help them solve challenges and support their role. When asked what challenges it would help solve, a range of challenges were given, but mostly centred on the time saving benefit that having all the data together in one place would help to quickly assess applications and sites/areas, which currently takes a long time.
- The summary page was identified as the most useful aspect of the DSS, providing the ability to quickly assess multiple sites at once without having to dig into detailed modules.
- A mixture of responses when asked what the least useful aspect of the DSS was, including: layer control and visualising multiple layers can get confusing, and being able to export data to excel or csv sheets would be helpful. However, for the most part users replied that there was no 'least' useful part of the tool.

When asked if they had any other comments, participants commented on the overall usefulness of the DSS and its potential to help

them and their teams. Many of the participants used the DSS as a basis for discussion between each other during the user testing workshop, to explore scenarios and discuss particulars of sites. This demonstrates how DSS interface can be used to facilitate collaboration and the generation of ideas/solutions by decision-makers and stakeholders. All stakeholder responses and comments are available in the supplementary material (S1 – Sheet 4).

Following user testing and feedback, seventeen specific potential improvements, changes, and modifications were identified. These included general improvements (n = 9) to the DSS user interface and functionality and improvements to the different modules and parts of the DSS: summary page (n = 2); Land Use Potential (n = 4); ground risk (n = 1); and economic evidence (n = 1).

Many of the potential improvements identified were not able to be implemented into the DSS due to them either being not technologically possible within the DSS prototyping platform, outside of scope for this stage of the prototyping process, or indeed outside of the scope of the DSS objectives. However, to illustrate what these improvements, changes, and modifications would look like once implemented, mock-ups were created. These can be found in the supplementary material (S3).

Improvements that were deemed possible and suitable to be implemented at this stage, were carried out. Doing this created a new version of the DSS. A full list of improvements, including details of *Implementability*, can be found in the supplementary material (S1 – Sheet 5).

4. Discussion

The DSS presented in this paper comprises both model-based, and information-based approaches (Supplementary Material, Fig. S5.6). These approaches are integrated using a modular based approach, where different areas of the decision problem (land use, ground risk, economics) are analysed in detail in separate modules. Each module utilises unique methodologies designed to enhance that specific area/topic, better supporting decision-makers.

The methods, approaches, and design of the DSS are underpinned by collaborative stakeholder engagement. Likewise, DSS outputs were designed in a manner that directly compliments stakeholder workflows user journey and addresses each problem statement (Section 2.1). The DSS outputs enable users to enhance, support, and/or challenge existing understanding or assessment of a site, a portfolio of sites, or an area. Users can interact with DSS outputs by several means to support a variety of decision-making activities. A range of data and report outputs could be included in a deployed version of the prototpye. The DSS could act as a platform from which to visualise a digital evidence base, as seen in other areas, such as virtual decision spaces (Bennett et al., 2023) and Planning Support Systems (PSSs) (Pettit et al., 2018). A summary report can prove useful for communication of findings and provision of evidence to non-expert audiences. The ability to export data to a spreadsheet report and/or spatial data export may be utilized to support internal analysis and the discovery of new understanding/scenarios and interoperability between the DSS and other software systems.

The DSS presented in this paper differs from many other such DSS reported in the literature. This DSS is unique in terms of its scope, degree of stakeholder involvement, user-focussed interface, and usability. As outlined in multiple previous studies (Bartke and Schwarze, 2015; Hammond et al., 2021; Huysegoms and Cappuyns, 2017), existing brownfield DSS research can be siloed in its approach, focussing on late-stage brownfield development issues, with a tendency to consider the environmental dimension of decision-making over socio-economic considerations. This gap has here been addressed by combining findings with large-scale stakeholder engagement (Hammond et al., 2023b) and through the development of a detailed use case (Section 2). Findings from the latter further reinforce the underpinning need for this area of decision support research, both from an academic/research context and in supporting public-sector decision-making needs.

The three modules of the DSS each provide support for challenging elements of decision making: spatial planning and land use assessment; understanding and planning for abnormal ground conditions; and establishing an understanding of likely economic viability of a site or area. In this research, these different aspects can be visualised alongside each other in one unified digital platform. This DSS has thus been designed to address these needs from stakeholder engagement with public sector decision makers and in turn addresses specific shortcomings of existing research. This novel DSS further provides a digital evidence base that can be shared to support decision-making in the early stages of regional brownfield planning and redevelopment.

The incorporation of stakeholder preferences, through well-designed stakeholder analysis and engagement, is crucial in digital tool development (Bartke and Schwarze, 2015). Existing DSS research is often not designed in a user-led manner and as a result suffers from a low degree of usability and user experience (Hammond et al., 2021, 2023b). This research demonstrates an improved method for DSS development, placing stakeholder engagement and user research at the centre of the process. To summarise, stakeholder involvement in this research has included: a sector wide survey to identify general problem statements (Hammond et al., 2023b); semi-structured discussion and interviews to develop a use-case; involvement in the development of Land Use Potential models; quality assurance in the development of user interface and DSS functionality; user testing of DSS to identify improvements; and implementation of DSS outputs through case-study application (Hammond et al., 2023a). Through involvement with stakeholders at each stage of the DSS development, the authors conclude that it achieves its intended objectives, with a high degree of potential usability, and is deemed useful by brownfield planning and redevelopment stakeholder to support their decision making.

Findings from user testing indicate that the decision support system presented here has a high degree of usability and is suitable for supporting stakeholder across a range of tasks. Overall feedback received from users was very positive, with many comments on the strengths of the DSS, its design and functionality. However, feedback and comments recorded during user testing did also identify several issues and areas for future DSS improvement. As suggested by stakeholder from energy and decarbonisation professionals, one area for future development could be the addition of modules focussing wider city planning challenges, in this case, assessing the decarbonisation potential of a particular site. The potential here being that a DSS, like the one presented, with a modular structure may become central platform to visualise many different aspects of land use decision making simultaneously (Beriro et al., 2022). This is a unique strength of the modular design approach, in that the system is ultimately adaptable and extensible, allowing for new developments, and further modules to be added. This allows the DSS to retain a flexibility in meeting shifting areas of concern for public sector and organisational decision making. For any new modules, comprehensive stakeholder engagement and research also should be conducted before development, ensuring that the addition of new models and data will be useful to visualise alongside the current DSS modules/outputs.

Many of these improvements consist of iterative changes to the user interface or interactivity of the DSS that when implemented will contribute to the final stages of DSS development, building on the initial prototype.

5. Conclusions

This paper has presented a novel prototype DSS capable of supporting early-stage, city-region and local scale, land use planning for brownfield redevelopment. The DSS was developed to address specific problems identified through extensive stakeholder engagement and builds on limitations observed in existing research of existing DSS identified from academic literature. The DSS has three modules, each of which focusses on a key aspect of decision making: (1) the Land Use Potential module presents an assessment of redevelopment potential for

five end-uses and uses a novel GIS-MCDA model; (2) the Ground Risk module presents a mapped quantification of ground risk posed by contamination and geotechnical instability; and (3) the Economic Evidence module presents a collation and enhancement of relevant datasets to support economic viability assessment. The key results of these modules are then integrated and presented in summary. The DSS presented is in the form of an ESRI WebGIS, with a user interface constructed using the ArcGIS Online Experience Builder platform. The design, methods, and functionality of the DSS were developed following comprehensive stakeholder engagement and ensured stakeholder involvement throughout development. This has ensured intended users of the DSS understand the underlying methods, preventing the DSS from becoming a 'black box'. This allows stakeholders to accurately interpret DSS outputs to decision-making as appropriate. Evaluation of the DSS was undertaken by means of extended user testing with a variety of public-sector stakeholder and policy makers from across a city region area. Results from this user testing indicate that the DSS has a high degree of usability, and that the interface and outputs can help to support stakeholders in their day-to-day land use planning decision tasks. This research illustrates good practice for the creation of modern, user-led, brownfield DSSs and addresses existing gaps in the literature.

Author contributions

E. Hammond: Conceptualization, Methodology, Analysis, Investigation, Writing-Original Draft, Visualisation, Validation, Data Curation. D. Beriro, F. Coulon, S. Hallett: Resources acquisition, Project Administration, Writing-Review and Editing, Supervision, Funding Acquisition. R. Thomas, D. Hardy, A. Dick, M. Dickens, E. Washbourn: Writing-Review and Editing.

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.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi. org/10.1016/j.jenvman.2023.119466.

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