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Research article

From data to decisions: Empowering brownfield redevelopment with a novel decision support system

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ABSTRACT

This research evaluates a novel decision support system (DSS) for planning brownfield redevelopment. The DSS is implemented within a web-based geographical information system that contains the spatial data informing three modules comprising land use suitability, economic viability, and ground risk. Using multi-criteria decision analysis, an evaluation was conducted on 31,942 ha of post-industrial land and around Liverpool, UK. The representativeness and credibility of the DSS outputs were evaluated through user trials with fifteen land-use planning and development stakeholders from the Liverpool City Region Comined Authority. The DSS was used to explore land use planning scenarios and it could be used to support decision making. Our research reveals that the DSS has the potential to positively inform the identification of brownfield redevelopment opportunities by offering a reliable, carefully curated, and user-driven digital evidence base. This expedites the traditionally manual process of conducting assessments of land suitability and viability. This research has important implications for assessing the impact of current and future planning policy and the potential for the use of digital tools for land use planning and sustainability in the UK and globally.

1. Introduction

Land is a finite resource, with urban land development posing significant challenges (Amato et al., 2016; Department for Science Innovation and Technology, Geospatial Commission, 2023). Around 4.4 billion people, 56% of the world's population live in urban areas, and this figure is expected to more than double by 2050 (World Bank, 2023). The growing population, coupled with rapid urbanization, intensifies the strain on urban spaces, resulting in urban sprawl, and overcrowding in urban centres impacting people and the environment (Guler et al., 2021; Shao et al., 2021). Developing underused and often derelict 'brownfield' (previously developed) sites can provide a policy-based approach to ease pressure on valuable 'greenfield' (undeveloped) land resources for housing, employment, and infrastructure (Green, 2018). For example, in England, the 2021 National Planning Policy Framework (NPPF) (MHCLG, 2021) and the Homes England Strategic Plan for 2023 to 2028 (England, 2023) urge local planning authorities (LPAs) to support the reuse of brownfield land to meet housing demand. There are similar policies in other countries around the world including the United States, Canada, Germany, and France. (Hou et al., 2023). Across the world there are estimated to be large areas of brownfield land that could be used for redevelopment, including 4.2 million potentially contaminated brownfield sites across the EU (Van Liedekerke et al., 2014), 500, 000 brownfield sites in the United States (Green, 2018), and an estimated 23,000 brownfield sites in the UK, equating to the potential for over 1 million new homes to be built (CPRE, 2022).

In addition to providing space for new homes, brownfield land is an important resource for biodiversity gains (Macgregor et al., 2022), green infrastructure (Otsuka et al., 2021) and employment (Pytel et al., 2021), providing an opportunity to help meet global needs for sustainable development and aligned environmental responsibility (European Union, 2010; The Land Trust, 2015; UNEP, 2020). In the UK, land

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developers and land use planners are encouraged to "identify and define those areas where land should be optimised for priority uses other than housing", advocating multi-functional land uses where possible (House of Lords, 2022). This serves to meet wider sustainability goals including social and biodiversity objectives (MHCLG, 2021) as well as the wider objective of placemaking. Placemaking aims to create inclusive, people-centred spaces that contribute to the social, cultural, economic, and environmental vitality of a community (Thomas, 2016).

Identifying and allocating land for development happens at multiple scales, this is driven by complex governance arrangements for land use planning, which divides plan-making responsibilities between national, regional, and local authorities. Land use planning is governed by a variety of legislation, policies, and guidelines. For example, in England, the Government sets out its planning policies in the NPPF (MHCLG, 2021), providing guidance on issues such as sustainable development, housing provision, transportation, and biodiversity. It outlines the key principles and goals that local planning authorities (LPAs) should consider when identifying land for future development. Regional planning is curated by regional bodies such as combined authorities (CA), some of which create regional spatial strategies to guide strategic development and land use.

In general, land use planners prepare development plans through a series of sequential steps (Department for Levelling Up Housing and Communities, 2021): (1) evidence gathering, consisting of collecting data and assessing existing conditions and needs of the area, (2) drafting the plan, based on the evidence gathered, considering national and local policies, including an evaluation of economic viability, (3) public consultation, where the draft plan is made available for public consultation, allowing individuals and organisations to provide feedback and suggest changes, (4) examination in public, where an independent inspector reviews the plan and conducts an examination in public, considering objections and representations from various groups, and (5) adoption, where after addressing any required amendments, the planning authority formally adopts, or rejects, the plan. As part of an NPPF compliant local plan development, LPAs review land available for development through targeted strategic assessments including Strategic Housing Land Availability Assessments (SHLAA), and Strategic Housing and Economic Land Availability Assessments (SHELAA). LPAs are also required to create and maintain a Brownfield Land Register (BLR) containing brownfield sites that are available, suitable and achievable for housing development, irrespective of their planning status (Ministry of Housing Communities and Local Government, 2017).

Land use planning for brownfield redevelopment is a complex and multifaceted process that involves engaging with a range of stakeholders. Decisions should be underpinned with a transparent evidence based informed by a range of data and models (Hewitt et al., 2014). Obtaining comprehensive and up-to-date data on various factors, such as the suitability of development land, ground conditions, and cost viability estimates can be challenging (Hammond et al., 2023). Incomplete or outdated data can hinder accurate analysis and decision-making, and predicting future land use requirements accurately can be challenging (DSIT and Geospatial Commission, 2023; Ren et al., 2019). Factors such as population growth and climate change introduce uncertainties that highlight the need to underpin decision making with a suitable evidence base (Hurlimann et al., 2021).

To support land use planning, digital tools can be used to enhance the efficiency of data analysis and visualisation, leading to a better understanding of the area under consideration (Jenks and Dempsey, 2006; Stratigea et al., 2015). Digital tools enable accurate and easy-to-understand representation of the local area, allowing planners to make more informed decisions (Stratigea et al., 2015). For example, geographic information systems (GIS) are now routinely used by planners for mapping and analysis of existing and new areas for development (Kahila-Tani et al., 2019). Digital consultation and engagement tools are also used by planners for communicating plans and policies to wider stakeholders and the public (Simonofski et al., 2021).

Within the brownfield redevelopment and land use planning literature, specialised digital tools called Decision Support Systems (DSSs) and Planning Support systems (PSSs) have been developed to aid land use planners and decision makers (Marcomini et al., 2009; Pettit et al., 2018). In this current research, we define these as systems that may comprise one or more *decision* support *tools* (DSTs), designed to enhance the value of data and information and increase the understanding of an issue or problem, often through decision analysis or spatial visualisation of the data (Hammond et al., 2021, 2023). There are numerous examples of brownfield DSSs and PSSs in literature (Hammond et al., 2021), but despite this, the uptake and regular use of these systems remains low, and several areas of improvement have been identified (Hammond et al., 2021, 2023; Pettit et al., 2018). There is a gap in the current literature for DSSs that address early-stage, regional scale, brownfield planning and redevelopment issues, and approach assessing post-industrial land, considering environmental, social, and economic dimensions simultaneously (Hammond et al., 2021). We believe this gap is the reason for a lack of DSS uptake.

Previous studies (Bartke and Schwarze, 2015; Bennett et al., 2023; Burinskiene et al., 2017; Hammond et al., 2021; Pelzer, 2017; Russo, 2017) have focussed on assessing the effectiveness of DSSs and PSSs for brownfield planning and redevelopment. These authors identified potential areas of improvement, firstly, the usability of the system, secondly, reducing excess complexity in terms of the input decisions users must make, thirdly, increasing functionality to match users/stakeholder expectations, and finally, enhancing interpretability by optimising the number of variables present within the decision analysis and adopting participatory approaches to development with the intended user base.

The primary focus of this research is to assess the effectiveness of a novel DSS, designed for early-stage city-region level land use planning and brownfield redevelopment and implemented within the geographical context of the Liverpool city region, UK; an area where brownfield redevelopment is crucial in supporting local development. The methodology used to create the DSS is presented in detail in a forthcoming study (Hammond et al., *In Review*), and follows a stakeholder-led approach where the overall design, development and testing process of the DSS incorporates stakeholder preferences and knowledge. The research objectives here are: (1) to test and verify the DSS outputs as accurate and reliable using qualitative and quantitative methods, and (2) to evaluate the potential impact of the DSS on land use planning decisions and policies by facilitating rapid assessments and evaluations of brownfield land suitability and viability.

2. Methods

2.1. Overview of the DSS

The methodology used to create the DSS and its outputs is described in detail in Hammond et al., (*In Review*). In summary, the DSS has three functional modules, all contained within an ESRI ArcGIS Online user interface (Fig. S1, Supplementary Material). These comprise: (1) Land Use Potential (LUP) for residential, commercial, greenspace, and mixed-use. These include an assessment map of a brownfield site/areas spatial planning potential, derived from GIS-based multi-criteria decision analysis (GIS-MCDA)), (2) Ground Risk, which presents soil and groundwater contamination and geotechnical risk maps, also derived using GIS-MCDA, and (3) Economic Evidence, which presents a collection of raw and derived spatial data to support economic viability assessment of brownfield sites. The DSS outputs from these three modules are attributed to 0.25 ha square-cells (LUP), and 0.25 ha hex-cells (ground risk) that cover an area comprising 31,942 ha of post-industrial land in the Liverpool city region, UK. These cells can be queried against individual spatial layers (e.g., land use potential for residential land use) by grid cell for the area of post-industrial land or via a portfolio of user-defined sites, where each site is attributed with the outputs from each module. For each spatial extent (e.g., potential development site) , two classifications are produced (1) Site Summary –

this is the mean LUP and max ground risk score as well as the sum value for economic viability evidence for all cells that intersect with the site, and (2) Site Detailed – this is a ‘clip’ of all the cells that intersect the site boundary (Fig. 1). These classifications allow the user to compare differences in scores within and between sites.

The land use potential module contains five GIS layers, one for each land use type (residential, small-commercial, large-commercial, greenspace, and mixed-use). The MCDA criteria used to create these layers were informed by planning officers working for the Liverpool City Region Combined Authority (Hammond et al., In Review). Each criteria within the MCDA model for each end-use was related to a spatial planning concept or policy adopted by LCRCA. For example, the criteria *proximity to town centre* was used to emulate the 15-min neighbourhood concept used currently by land use planners. The ground risk scores were provided for the purpose of this research by Groundsure as part of their ‘Groundscreen’ data product (Groundsure, 2023). The Groundscreen methodology is unable to be described here due to commercial sensitivities but is underpinned by a GIS-MCDA methodology that uses a range of environmental and geological spatial data (e.g., historical land use). The economic evidence module comprises three datasets: (1) estimated remediation costs for contamination and geotechnical hazards (also from ‘Groundscreen’), (2) estimated land value for each site (derived from publicly available data (MHCLG, 2020a)), and (3) estimated new build property total sale price (derived using recent transaction data (HMLR, 2023)).

2.2. Selection and evaluation of study sites

The study sites selected for evaluation comprise: (1) post-industrial land in the Liverpool city region, including (2) a portfolio of SHLAA sites within post-industrial land in the Liverpool city region and, (3) the St Helens Local Plan development areas for housing and employment (St Helens Borough Council, 2022) (Fig. 2). All DSS outputs were generated for these study sites and analysed using ESRI ArcGIS Pro tools to identify trends and patterns with the aim of understanding development potential for the Liverpool city region. This included comparing the distribution, variance, and reasons for any underlying similarities/differences for LUP classifications, ground risk scores, and economic evidence values.

Post-Industrial Land (PIL) for the city region comprises an area of approximately 31,942 ha (~315 km^2) with former/current industrial centres in Birkenhead (Wirral), Runcorn (Halton), St Helens, and Liverpool city having the most densely concentrated areas of post-industrial land (Fig. 2). PIL was created in a GIS using historical land use data to identify areas that have been previously developed or affected by human activity; this comprises 43.5% of the total Liverpool city region area (Hammond et al. *In Review*).

The SHLAA land comprises 2,783 sites (6,185.3 ha) (Fig. 2) and was provided in GIS format for this research by *LandTech (*https://land.tech/*)*. The majority of the SHLAA sites (93%) fall within the post-industrial land. The size and distribution of these sites 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 (Table 1).

The St Helens local plan was adopted in July 2022, and will extend until 2037. As part of the local plan land has been allocated for future housing (16 sites; 1,159 ha) and employment (8 sites; 1,033 ha) (Fig. 2). These areas were digitised into GIS layers and used to produce DSS outputs.

Two workflows were used to evaluate post-industrial land, local plan allocations and SHLAA sites: (1) apply the DSS to the post-industrial land and local plan allocations, (2) verify the DSS outputs for SHLAA and BLR study sites using qualitative and quantitative methods.

2.2.1. Quantitative verification of land use potential

Quantitative verification of the DSS involved comparing the five-land use potential (LUP) models, with real-world sites of the same existing or potential land use type (Table 2). The verification process was conducted as follows: (1) real-world comparison sites were identified using internet research and polygonised in a GIS, (2) LUP outputs were created for these comparison sites, in both site detailed and site summary views, (3) the 6 LUP categories were reclassified as binary outcomes (positive/negative), (4) a GIS-based comparison between LUP models and real-world verification comparison sites was conducted.

For residential land use potential, comparison was undertaken using two publicly available potential housing datasets: Brownfield Land Register (BLR) sites, and SHLAA sites. The same verification process was undertaken for the remaining four land use types (Commercial, Greenspace, and Mixed-Use), and sites identified using a combination of aerial imagery within ArcGIS Pro, OpenStreetMap mapping, and existing spatial datasets (Table 2). In total, 43 large-commercial sites, 223 areas of small-commercial development, 1,298 greenspace sites, and 61 areas of mixed-use development were identified for use in the verification process.

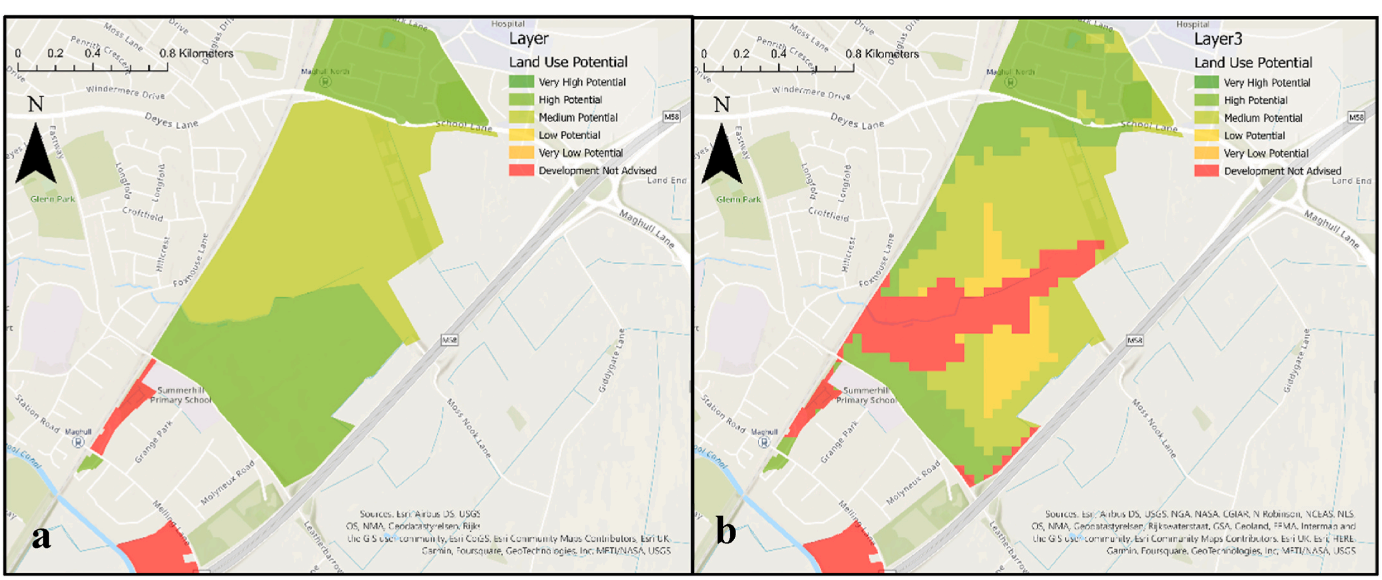

Fig. 1. Example of site summary (a) a site detailed (b) views.

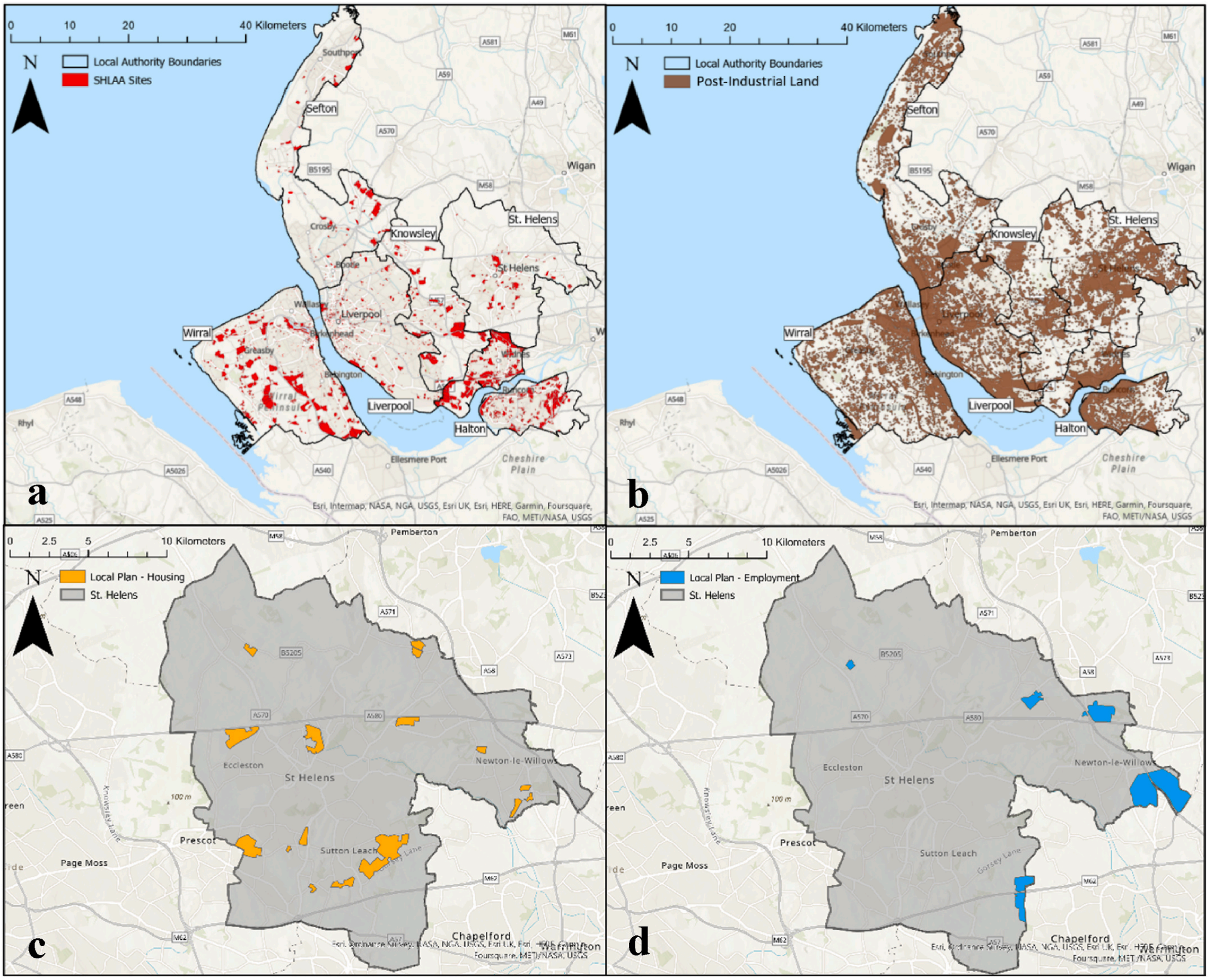

Fig. 2. Liverpool city region showing the distribution of SHLAA sites (a), post-industrial land areas (b), and St Helens local plan development areas (c, d).

Table 1
Size and distribution of case study sites and post-industrial land within the Liverpool City Region Authority.

Local Authority	Case-study sites			Post-industrial land	
	Number of sites (Count)	Percentage of total (%)	Mean site area (ha)	Area (ha)	Percentage of total (%)
Halton	525	19	3.6	3,827.4	12
Knowsley	201	7	3.8	3,106.9	10
Sefton	129	5	4.3	5,653.4	18
St. Helens	126	2	2.4	6,004.5	19
Liverpool	977	35	0.5	6,304.9	20
Wirral	825	30	2.5	6,686.0	21

The DSS LUP output scores range from 0 to 1 (Table 3). These scores were reclassified into binary outcomes for this study, with higher scores indicating positive suitability for that land use. Categories were assigned to each LUP score range (Table 3). For the SHLAA and BLR sites, the positive/negative classification was used to compare the DSS results with the formal LPA SHLAA outcome results.

Using a GIS attribute table, simple mathematics and the field calculator, the LUP outcomes (positive or negative) were compared to real-world verification comparison sites, and the percentage of agreement was calculated and presented in Section 3. If the LUP models are accurate and representative of real-world decision making, there should be a strong agreement between LUP model outputs and verification sites.

2.2.2. *Qualitative verification of sites using local expert knowledge*

Qualitative verification of the DSS outputs for 11 SHLAA sites was conducted by comparing the results with local experts with knowledge of those sites. This user-based testing was undertaken during a facilitated workshop with fifteen individuals working for the Liverpool City Region Combined Authority on 29th and 30th November 2022. During each session, the workshop participants were shown how to use the DSS and were asked to select sites they were familiar with and compare the DSS outputs to their knowledge and experience with these sites. Feedback was recorded using responses to a standardised set of questions and notes from discussions (Supplementary Material, Table S6).

The agreement between the DSS outputs and the experts expectations and knowledge of the sites was recorded, noting circumstances where the outputs produced by the DSS matched/did not match the participants knowledge of that particular site or area. This comparison was designed to test if the land use potential models, ground risk outputs, and synthesis of economic evidence, were believed by the users to

Table 2
Sites used for land use potential verification.

Land use potential	Verification comparison site	Source
Residential	SHLAA Sites BLR Sites	Local Authority Records (compiled by LandTech)
Small-Commercial	Existing local shops, small retail parks	OpenStreetMap, Aerial Imagery
Large-Commercial	Existing industrial land, factories, warehouses, large retail parks	OpenStreetMap, Aerial Imagery
Greenspace	Existing greenspace, parks, recreation fields, sports grounds	OpenStreetMap, Aerial Imagery, OS Open Greenspace
Mixed use	Existing mixed-use developments, Residential land and/or shops and/or greenspace	OpenStreetMap, Aerial Imagery

The LUP model scores were generated for the real-world comparison sites. This was undertaken to account for within and between site similarities and differences for land portfolio assessments.

Table 3
Land Use Potential categories based on outputs from the DSS.

Land Use Potential Score	Land Use Potential Classification	Positive/Negative Outcome
0.80–1	Very High Potential	Positive (suitable)
0.60–0.79	High Potential	
0.40–0.59	Medium Potential	
0.20–0.39	Low Potential	Negative (not suitable)
0.01–0.19	Very Low Potential	
0.00	Development Not Advised	

be accurate and representative of current real-world conditions.

3. Results

3.1. Liverpool city region

The Liverpool City Region Combined Authority (LCRCA) area (Fig. 3) was used to evaluate the DSS and to demonstrate its practical application and current use case. The city region is located in northwest England and covers an area of approximately 723 km^2. Liverpool has a significant industrial history as a major port and trading hub in the 18th and 19th centuries which led to its surrounding areas now having numerous urban and peri-urban brownfield sites that are potentially affected by contamination and/or geotechnical land stability issues (Ridgway et al., 2012).

The Liverpool City Region (LCR) has a greater prevalence of deprivation than the UK national average across all domains of deprivation (MHCLG, 2019), with 1 in 3 of LCR neighbourhoods being in the 10% most deprived nationally (LCRCA, 2020), and this is reflected in lower than average house and land prices (LCRCA, 2020). As a result of this, brownfield sites in the city region, are more likely to suffer from deliverability issues, whereby costs to clean up and develop sites prevent them from being economically viable due to low land and house prices.

The LCRCA is a mayoral devolved administration responsible for six local authorities (Liverpool, Sefton, Knowsley, Halton, St. Helens, and

Fig. 3. The Liverpool city region and its six constituent Local Authorities.

Wirral) (Fig. 3). LCRCA is responsible for strategic planning and regeneration across the city region, as well as transport, innovation, business growth and support, energy, and culture. LCRCA is developing a new Spatial Development Strategy (SDS) which is a strategic land use plan that allocates areas for housing, economy and employment land (LCRCA, 2023). To support the development and implementation of the SDS, LCRCA is exploring the use of digital tools and evidence bases to support land use planning decisions.

3.2. Quantitative verification of land use potential

3.2.1. Residential land use

There is a good level of agreement between the LUP model and actual residential sites (Table 4). The verification process revealed that the LUP performs well in identifying suitable areas for residential development. For residential land use potential, the verification process showed a very high level of agreement with ~94% agreement between the LUP model and verification test sites (SHLAA/BLR). However, it also shows that the model struggles to identify areas that are unsuitable for residential development, as well as a few instances where the 'positive outcomes' differ from actual outcomes.

To investigate the discrepancies between the LUP model and real-world residential sites, an analysis was conducted on the SHLAA assessment reports from LCRCA LPAs for six sites. These sites were chosen because the LUP model disagreed with the SHLAA assessment. For SHLAA sites with a positive outcome but LUP model designation of 'Negative,' the analysis found that the disagreement was due to the real-world assessment considering factors not currently incorporated into the MCDA model or factors that cannot be incorporated, such as local attitudes to development, local political strategy, and site-specific viability. For example, the Halton SHLAA site H1630 was assessed as deliverable in 0–5 years, but the report noted that the site was geographically isolated and would require improved connectivity. For SHLAA sites with a negative outcome but an LUP model outcome of 'Positive', the analysis found that the disagreement was due to the real-world assessment considering factors not considered by the LUP model. For example, the St Helens SHLAA site 79 was identified as positive by the LUP model but was assessed as negative for SHLAA assessment because it was being actively pursued by developers for retail and leisure rather than residential.

3.2.2. Other land use types

Results also show a very high level of agreement between the other LUP models and verification test sites (Table S1, Supplementary Material). For each land use type (Large Commercial, Small Commercial, Greenspace, and Mixed-Use) the verification process has shown a close to 100% agreement for each land use type. This indicates that the LUP models are effective and accurately represent the decision-making process in real-world land use planning.

Overall, the quantitative verification process demonstrated a high level of agreement between the DSS outputs and LPA proposed land use for various end-uses. Differences between the LPA and DSS results may indicate the need for further refinement and enhancement of the model to better align with real-world assessments and decision-making processes in brownfield land use planning.

Table 4
Results from verification of residential land use potential GIS-MCDA models.

Site Type	Agreement (%)	
	Positive Outcome	Negative Outcome
When Positive outcome is Medium Potential or above		
SHLAA – Site Summary	94	34
SHLAA - Site Detailed	82	67
BLR – Site Summary	93	N/A
BLR – Site Detailed	84	N/A
When Positive outcome is Low Potential or above		
SHLAA – Site Summary	97	30
SHLAA - Site Detailed	86	62
BLR – Site Summary	96	N/A
BLR – Site Detailed	84	N/A

3.3. Qualitative verification of potential housing sites using local expert knowledge

During the workshop, the DSS was used to evaluate a total of 11 participant-selected sites (Table S2, Supplementary Material). The attendees assessed the land use potential, ground risk, and economic evidence for each site, to determine the underlying factors driving a particular score or classification. The attendees found that the DSS outputs accurately matched their understanding and expectations for each brownfield site.

The results (Table S2, Supplementary Material) show that for each of the 11 sites, the outputs from each DSS module (Land use potential, ground risk, and economic evidence) matched the attendee local expert knowledge for that site. There was only one deviation from this; a stakeholder in session 3 found that when reviewing the estimated total property sale price for study site *2553,* the estimation was greater than expected. The reason for this was investigated during the workshop and revealed to be that the assumed dwelling/ha density for that site was greater than the project capacity for the site, leading to a higher than expected estimate presented by the DSS. The stakeholder did however confirm that the price estimation to estimated dwellings/ha ratio was reasonable for that site and wider area.

3.4. Evaluation of post-industrial land and study sites

3.4.1. Land use potential

The DSS LUP potential module was applied to post-industrial land and study sites in the Liverpool city region (Table 5).

Residential: For residential LUP, 55% (17,370 ha) of post-industrial land in the city region is classified as high or very high potential for residential use, and 35% (11,054 ha) of post-industrial land is classified as Development Not Advised due to being within Flood Zone 3 or in Greenbelt (Fig. 4). This restricts the suitability of large areas of the city region for residential development. However, for the portfolio of case study sites analysed, residential land use potential assessment scores 86.5% and 98.8% for detailed and summary classification, respectively. This indicates that the portfolio of SHLAA is within areas of high development potential within the city region and provides quality residential land.

Small-scale commercial: The LUP results show that for small-scale commercial development, 82% (25,898 ha) of post-industrial land in the city region is considered to have medium potential or above. In the case of the specific sites examined in the study, 94% of them received a medium potential or above classification. This indicates strong potential/suitability across the city region for small-commercial development.

Large-scale commercial: The DSS showed that for large-scale commercial development, 76% (24,003 ha) of post-industrial land has a high or very high potential for large-scale commercial development. However, when the minimum size requirement (4 ha) was applied (Hammond et al., *In Review*), only 12% (3,789 ha) of the study sites achieved medium potential or above. This still indicates that a significant proportion of land in the city region could be suitable for large-commercial development.

Greenspace: Although 92% of post-industrial land is classified as medium potential or above for greenspace development, there are small variations in the classification between the city region (86.5%) and the case-study sites (98.8%), indicating very strong redevelopment potential for the inclusion of greenspace development across the city region's post-industrial land, in addition to the other land uses.

Table 5
Land use potential assessment, values rounded to the nearest whole number.

Land use Potential Category	Land use Potential Score	Post-industrial land	Study Sites (Detailed)	Study Sites (Summary)	Local Plan - Housing	Local Plan - Employment
Residential (% of area/sites)						
Very High Potential	**0.8–1**	35 (11,369 ha)	18	60	3	n/a
High Potential	**0.6–0.8**	21 (6,632 ha)	21	15	35	n/a
Medium Potential	**0.4–0.6**	7 (2,210 ha)	0	7	43	n/a
Low Potential	**0.2–0.4**	2 (631 ha)	2	3	15	n/a
Very Low Potential	**0–0.2**	0 (0 ha)	4	1	0	n/a
Development Not Advised	**0**	35 (11,054 ha)	55	14	4	n/a
Small-Scale Commercial (% of area/sites)						
Very High Potential	**0.8–1**	28 (8,843 ha)	16	50	n/a	n/a
High Potential	**0.6–0.8**	34 (10,738 ha)	28	31	n/a	n/a
Medium Potential	**0.4–0.6**	19 (6,001 ha)	30	14	n/a	n/a
Low Potential	**0.2–0.4**	11 (3,474 ha)	20	4	n/a	n/a
Very Low Potential	**0–0.2**	8 (2,527 ha)	6	1	n/a	n/a
Development Not Advised	**0**	0 (0 ha)	0	0	n/a	n/a
Large-Scale Commercial (% of area/sites)						
Very High Potential	**0.8–1**	24 (7,580 ha)	9	1	n/a	0
High Potential	**0.6–0.8**	52 (16,423 ha)	37	8	n/a	33
Medium Potential	**0.4–0.6**	18 (5,685 ha)	18	3	n/a	34
Low Potential	**0.2–0.4**	5 (1,579 ha)	2	1	n/a	24
Very Low Potential	**0–0.2**	1 (316 ha)	1	0	n/a	9
Development Not Advised	**0**	0 (0 ha)	34	87	n/a	0
Greenspace (% of area/sites)						
Very High Potential	**0.8–1**	17 (5,369 ha)	20	36	n/a	n/a
High Potential	**0.6–0.8**	47 (14,844 ha)	5	44	n/a	n/a
Medium Potential	**0.4–0.6**	28 (88,436 ha)	62	19	n/a	n/a
Low Potential	**0.2–0.4**	8 (2,527 ha)	13	1	n/a	n/a
Very Low Potential	**0–0.2**	0 (0 ha)	0	0	n/a	n/a
Development Not Advised	**0**	0 (0 ha)	0	0	n/a	n/a
Mixed-Use (% of area/sites)						
Very High Potential	**0.8–1**	25 (7,896 ha)	14	48	n/a	n/a
High Potential	**0.6–0.8**	36 (11,370 ha)	29	32	n/a	n/a
Medium Potential	**0.4–0.6**	22 (6,948 ha)	36	15	n/a	n/a
Low Potential	**0.2–0.4**	14 (422 ha)	19	5	n/a	n/a
Very Low Potential	**0–0.2**	3 (947 ha)	2	0	n/a	n/a
Development Not Advised	**0**	0 (0 ha)	0	0	n/a	n/a

3.4.2. Ground risk

Ground risk scores for the Liverpool City Region are presented in Table S3 (Supplementary Material). The mean risk score for contamination for the site summary view is 0.12 and 0.07 for the detailed view. The summary score for each case-study site is calculated by taking the maximum score from cells within that site. The maximum risk score for post-industrial land is 0.91, with a mean score of 0.12. For the geotechnical risk score, the mean score for the summary view was 0.12, and 0.10 for the detailed view. For post-industrial land, the mean score was 0.12. There is a significant variation in the contamination and geotechnical risk scores for post-industrial land across the city region. Areas with a history of industrial use, such as St Helens, Birkenhead, Liverpool docks, Runcorn, and Widnes, have considerably higher risk scores than the rest of the city region. Fig. S2 (Supplementary Material) illustrates the distribution of contamination risk scores for post-industrial land across LCR.

3.4.3. Economic evidence

A summary of the Economic Evidence module results for the study (SHLAA) sites is provided in Table S4 (Supplementary Material). The estimates for remediation costs, both for contamination and geotechnical issues, vary across the post-industrial land of the Liverpool city region. As with the ground risk scores, areas with a history of industrial land use require higher costs per hectare to remediate. Moreover, the land value estimates and estimated new build property price per square metre also show considerable variation across the city region. Certain areas of post-industrial land are considered more valuable based on their geography or past property transactions within the last five years (Fig. 5). The distribution of estimated values for case-study sites is highly variable since the value estimation is dependent on the site size. Additionally, the distribution of estimated land values and new build property total sale price (for houses and flats) also varies based on the location and area of the site.

The distribution of land value and projected property sale price closely aligns with areas of high deprivation, where sites are likely to suffer from viability and deliverability issues as a result. For example, for the Lower Super Output Area (LSOA) *Wirral 008C*, is within the top 20% most deprived area in LCRCA, and the average house price per m^2 is £488 per m^2, placing it in the bottom 5% in LCRCA in terms of property value. LSOA Wirral 008C is also situated in an area of high ground risk, and therefore increased estimated remediation costs for contamination, with an estimated clean-up cost of between £715,000 and £1,700,000 per hectare, the highest estimation bracket within LCRCA. This demonstrates the use of the DSS for identifying sites and areas with high potential for viability issues caused by underlying ground conditions or unfavourable local economic conditions.

3.5. S t Helens Local Plan – housing and employment land

3.5.1. Land use potential

The residential LUP assessment of the St Helens Local Plan housing allocations shows that 81.3% (25,679 ha) of the land was classed as medium LUP or above (Table 5). This reinforces that these areas are potentially suitable for residential development and could enable the

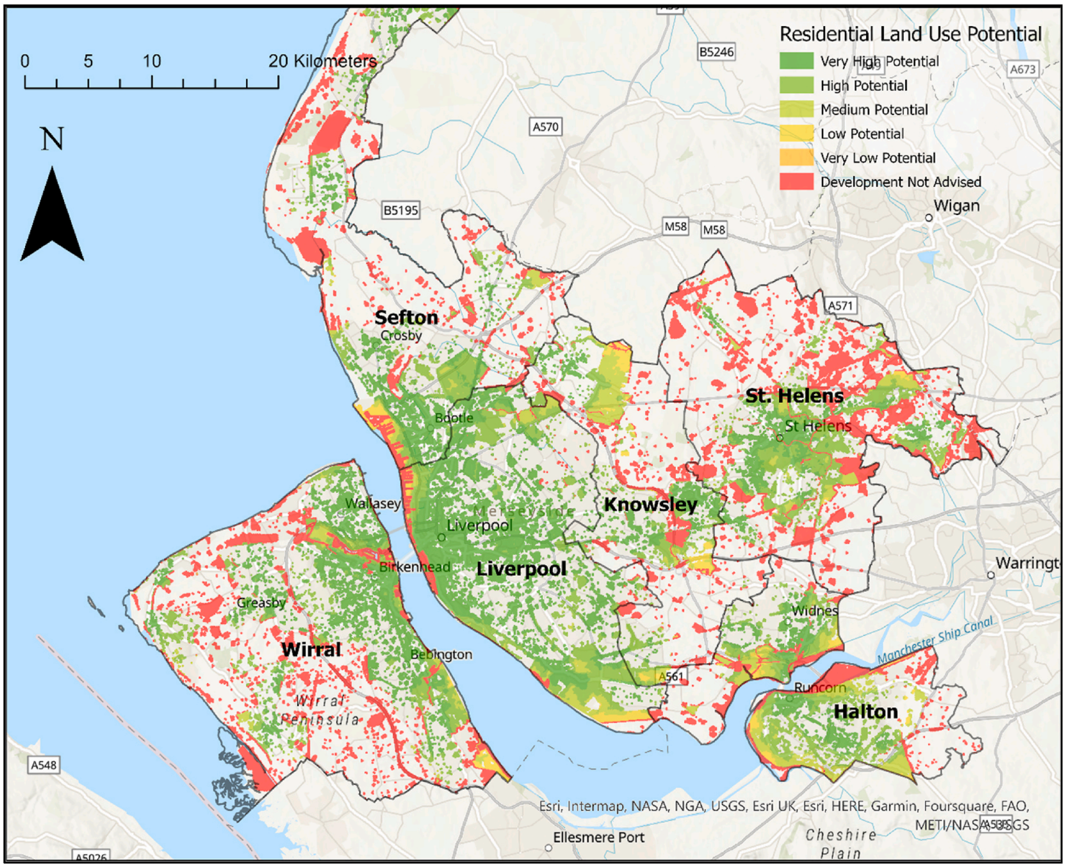

Fig. 4. Residential land use potential for LCR post-industrial land.

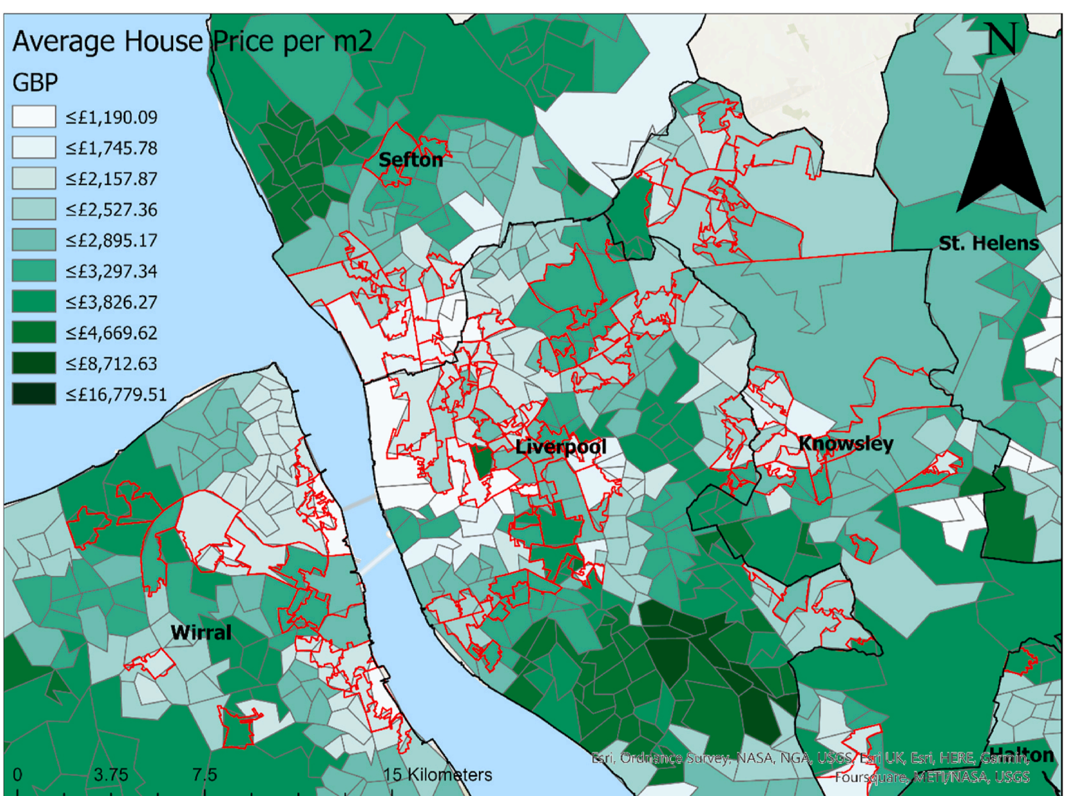

Fig. 5. LCRCA post-industrial land new build house prices per m^2 overlain by the top 20% most deprived areas in LCRCA.

delivery of some ~6,500 new homes. However, Site 4HA (*Land bounded by Reginald Road)* allocated for 2,988 homes (~361 ha) shows a deviation from the DSS results, with the majority of the site being assessed as having low potential for residential (Fig. S3, Supplementary Material). This result was influenced strongly by the location of the site being next to existing industrial land and its distance from existing local amenities and local centres.

An assessment of employment land allocations using the large-scale commercial LUP model shows that 66.5% (21,002 ha) of the area was classed as medium or high potential, with 33.5% (10,580 ha) of the land for employment areas being classed as low or very low.

3.5.2. Ground risk

Results from the ground risk module of the DSS show that local plan development areas for St Helens show, hotspots, where ground risk scores for contamination and geotechnical hazards are higher than average when compared to the rest of Liverpool City Region as a whole. For example, for the housing policy area, 6HA, (Land East of City Road), elevated values can be seen in both contamination risk and geotechnical risk scores (Fig. S4, Supplementary Material).

3.5.3. Economic evidence

Results from the economic evidence module for the St Helens local plan for housing and employment land are surmised in Table S5 (Supplementary Material). Due to their large area, the estimated economics of the St Helens local plan policy areas for housing and employment show very high-cost values when compared to other areas of LCR. However, extensive former industrial land use in St Helens means that the average estimated remediation costs for both contamination and geotechnical hazards are very high, ~£75 m and ~£1 m respectively. Due to the large areas available for development, the estimated total sale price for houses is also very large, whereby even the smallest site in the portfolio (7HS - Land South of Elton Head Road; 8.3 ha; 84 housing units) has a potential property sale price of ~£25 m. Estimated land value for local plan development areas also shows high values (Fig. S5, Supplementary Material), with the average residential land value for house areas as ~£80 m, and the average land value for employment land as ~£62 m.

4. Discussion

4.1. Evaluation and verification of the DSS

The DSS provides an evidence base to support assessments of brownfield redevelopment potential in the Liverpool city region for a range of land uses. The results (section 3) demonstrate that the DSS can provide support in justifying or challenging the identification and zoning of areas for certain types of developments for local authorities to meet their policy objectives. For example, LCRCA post-industrial land shows very high potential for greenspace development. Outputs produced by the DSS can help local authorities within LCRCA identify post-industrial land in their areas that could function as greenspace and green infrastructure helping to achieve sustainable development and biodiversity targets.

Use of the DSS outputs to assess the St Helens local plan development areas provides a digital evidence base to that could be used to support decisions made on the local plan, helping to support future decisions/amendments to the local plan. It is noteworthy that most of the local plan housing and employment development areas are within areas formerly protected as greenbelt land. St Helens Borough Council has justified their decision to develop within the *greenbelt*, to meet housing and employment land needs within the local authority, whilst also creating new areas for greenbelt designation (St Helens Borough Council, 2022). Overall, the LUP outputs support the St Helens Local plan housing and employment area allocations, although there is some variability within the larger sites. This perhaps indicates that further consideration of other factors (e.g., new road development nearby) is needed when specific planning applications are to be put forward to develop sub-areas of the local plan development areas. Early identification of ground risk using the DSS outputs provides evidence for additional intra-site zonation for land use planning purposes and enables prioritisation of resources to investigate/remediate contamination and geotechnical hazards on site, as specified by the local plan (St Helens Borough Council, 2022).

When combined with a review of ground risk scores and appraisal of economic evidence, the DSS results aid in identifying areas that might require interventions to 'unlock' either through remediation or economic interventions/funding, as well as understanding some of the potential early challenges that may arise for a scheme in terms of viability and deliverability. For example, the large areas allocated for development by St Helens Borough Council have the potential to provide substantial economic benefits for the area, where large parts are within the top 20% most deprived in Liverpool. However, due to underlying ground risk issues, large economic support might be needed to remediate and develop these sites to *unlock* their economic potential. The outputs produced by the DSS could support evidence-based decision making and the communication of development scenarios by presenting easy-to-understand early-stage estimations of development potential, costs, and risk for sites where viability may be an issue. Using the DSS, key stakeholders can be engaged in discussions at an early stage to explore routes to delivery as part of a circular economy approach to efficient land resources (Gallego-Schmid et al., 2020).

The GIS-MCDA models within the land use potential module of the DSS have revealed a strong agreement with real-world land use planning decision-making. The discrepancies identified highlight the limitations of the DSS model in capturing certain contextual factors and real-world considerations that can influence land use planning decisions. Factors such as local attitudes and political strategies and how they might affect site-specific viability can play a significant role in determining the suitability of a site for development. User feedback, along with qualitative verification, confirms that the DSS provides users with the intended data and evidence to support their assessments of brownfield land in their area of interest. The DSS was designed for use during the initial planning phases of development, however, user testing based verification uncovered several other potential alternative use cases. In summary: (1) supporting discussion between stakeholders leading to new planning/development decisions, (2) increasing ease of data management and access, (3) supporting community-led housing partnerships by enabling starting point to develop applications and projects with public sector organisations and community developers, and (4) evaluating assumptions in planning and funding application by comparing values produce by the DSS to those put forward by developers of applicants for planning permission. The evaluation and verification of the DSS demonstrate the overall applicability of the DSS and development approach for supporting land use planning stakeholders in public sector organisations.

This research demonstrates that the co-design of the MCDA and other data-driven factors affecting land use decision making can be reliably applied to a current worked example. The approach taken to developing the tool is consistent with wider planning objectives and challenges both in the UK and internationally (Crook and Whitehead, 2019). The selection of national scale and mainly freely available, open source, datasets provide scope for application to similar settings in the UK and potentially other countries around the globe. Similar datasets would need to be sourced for the application of the DSS to international examples, where the data themes required exist for most countries (Nirandjan et al., 2022). Before the DSS can be implemented into new areas, the LUP criteria/weighting, in particular, would need to be verified and checked by local expert land use planning stakeholders and refined, as needed, to represent the changing spatial planning priorities of that area (Albrechts et al., 2019; Wang et al., 2022). Alternatively, user-defined modelling of land use potential would allow the user to select criteria of their choice and weighted them as they deem appropriate, creating a bespoke assessment for each user's needs. Examples of this are seen in research evaluations of policy alternatives for urban planning using an online multicriteria decision analysis tool (Larsson et al., 2018).

Currently, it is difficult for land use planners considering a large number of sites to obtain digital evidence for ground risk, viability, and suitability for developments, with different conditions and for various scenarios. The utilisation of the DSS allows for early-stage screening of estimation of risk scores, financial information, and development potential contributing to the shared evidence based needed to produce regional and local strategic land use plans, such as the LCRCA SDS. The use of the DSS allows for the projection of the development model across the entire Liverpool region allowing LCRCA to quickly assess the factors influencing viability of development scenarios whilst remaining mindful of the LPAs priorities and constraints. Flexibility in the DSS workflow allows for the addition of new datasets and rules as new or revised user requirements are established. Finally, the use of the prototype DSS has the potential to improve consistency with data collection and data sharing by LCRCA within their organisation to the constituent LPAs, partners, and the public in a way not currently possible.

A practical example of where the DSS can actively support decision making is the current application of the outputs to a bid by LCRCA to the UK Government Brownfield Land Release funding, Round 2 (BLRF2) (Local Government Association, 2023). LCRCA used the DSS to support the assessment of BLRF2 sites by investigating the scale of some of the challenges (LUP, ground risk and economic viability) facing their current pipeline of brownfield sites. The DSS provided a supporting evidence base for the funding application and could be used to assess individual applications for regional brownfield funding should the bid be successful.

The DSS provides multiple added benefits to existing land use planning processes including, (1) the 'sense checking' of assumptions in planning applications, including constraints and abnormal factors affecting the deliverability of sites, (2) supporting the creation of a shared digital evidence base, (3) the identification of sites/areas within post-industrial land, that are potentially suitable for a range of land use types, and (4) acting as a collaboration platform, where data, models, and scenarios can be visualised by multiple stakeholders within a virtual decision making environment. This last point is recognised by others are being able to facilitate discussion, debate, and shared decisions making (Bennett et al., 2023).

Several limitations and areas for improvement were identified during this research. Firstly, the spatial data used in the tool need to be maintained and updated. This may prove a particular influence on datasets within the economic evidence module, where source datasets are regularly updated to reflect current economic conditions. Secondly, assumptions relating to the study area are built into the LUP models, this includes the specific criteria chosen, and weightings applied to the criteria. The criteria selection and weightings applied in the MCDA model are subject to potential bias and assumptions. During user testing based verification of the DSS, users self-reported that the DSS outputs aligned with their expertise and experience. It was noted that this as such, could have been subject to interview bias or response-shift bias where participants could potentially skew their responses in favour of reporting positive outcomes, or responses similar to other participants during interviews/assessments and workshops, a phenomenon reported by Howard and Dailey (1979). Identification of the limitations provides aides for future enhancements or refinements (e.g., adjusting stakeholder consultation methods) of the DSS and development process.

4.2. Policy implications

In the brownfield planning and redevelopment sector, the need for innovative digital tools is both a response to new policies but also an academic motivation to progress in the field (Hammond et al., 2023). The recent UK Levelling Up and Regeneration Bill, aims to improve the planning system by fully digitalising it and encouraging the use of digital tools to produce spatial development strategies (DLUHC, 2022a,b,c). This is proposed to be achieved through changes to regulations, national policy, guidance, and wider support for decision-makers. The bill encourages the development of new planning software and digital tools to bring the planning system into the 21st century, as outlined in the Planning for Future White Paper (MHCLG, 2020b). The UK Digital Strategy Policy Paper and National Planning Policy Framework also support the use of digital tools in decision-making processes. Internationally, the United Nations 2030 Agenda for Sustainable Development and the European Union's Urban Agenda also encourage the use of digital tools to support sustainable development (United Nations, 2023). Of these, Sustainable Development Goal 11 is focussed on the development of sustainable cities and communities, with several sub-goals encouraging members to consider the impact of urban development on the environment, and society, ensuring the development of future-proof cities, also aligning with the concepts of sustainable remediation developed by SuRF UK (CL:AIRE, 2021). Similarly, under the Urban Agenda for the EU, the use of digital tools to support sustainable development is encouraged under the themes: Sustainable use of land and nature-based solutions; and Digital Transition (European Commission, 2023a). Additionally, the longstanding 'no net land take' policy established by the European Commission, has been strengthened by the '*Soil Mission*' for 2030 (Decoville and Feltgen, 2023; European Commission, 2021). The strategy details the member states need to define objectives to reduce net land take by 2030, at national, regional, and local levels. The re-use of post-industrial land is a crucial part of this strategy (Decoville and Feltgen, 2023). The soil mission (as of June 2023) is currently encouraging the development of digital tools to support 'no net land take' and the re-use of land through funding initiatives (HORIZON-MISS-2023-SOIL-01-06: Soils in spatial planning) (European Commission, 2023b).

The DSS presented in this work could support UK planners and other public sector stakeholders in addressing the objectives of the levelling up and regeneration bill, policy-driven initiatives, sustainable development goals, and the move towards smart cities (European Commission, 2022). The DSS outputs and application to the study area demonstrate that the development of new software and digital tools can support sustainable placemaking, and strategic planning, and enable the development of much-needed land resources. The incorporation of digital tools (like this DSS) to assess land use planning options and the revitalization of post-industrial land aligns well with existing policies and initiatives within the framework of sustainable development (encompassing social, environmental, and economic factors). These policies and initiatives actively promote the adoption of digital tools, GIS, and map-based assessments by land use planning stakeholders to enhance their decision-making processes.

Future policy making should seek to establish specific guidance for the development of digital tools to support the redevelopment of post-industrial land. This future guidance should include policies to: (1) encourage the incorporation open-source data in digital planning tools ensuring that the input data is easier to find, understand, use and trust (DLUHC Department for Levelling Up Housing and Communities, 2022); the majority of underlying data used to create the DSS is derived from open-source data demonstrating the level of capabilities that can be achieved with publicly, available open-source data; (2) encourage collaborative user-led partnerships involving, academic research institutions, private sector organisations and public-sector decision makers for the co-creation of digital tools, aligning with recommendations from the Geospatial Commissions *Finding Common Ground* report (DSIT and Geospatial Commission, 2023), and (3) promote the creation innovative digital tools specifically for early-stage planning and assessment of brownfield land. This will allow stakeholders to make better-informed decisions on the future of sites that face deliverability challenges, meaning that development schemes are less likely to stall and that the final function of the site will better serve the local community, directly aligning with the UK digital planning reform (DLUHC, 2022b), NPPF (MHCLG, 2021), and goals of the Levelling Up agenda, to enable sustainable development in areas targeted for growth in the UK (DLUHC, 2022a).

5. Conclusions

This research demonstrates the usefulness and efficacy of a new DSS developed using a stakeholder-led participatory approach. The DSS was specifically designed to assist city region scale land use planning and brownfield land assessment, focusing on the Liverpool city region as a demonstration of application. The verification of the DSS has confirmed its suitability for use in brownfield decision-making as its outputs closely align with the expected or actual outcomes in real-world scenarios. The development and demonstration of this innovative spatial decision support system is a valuable addition to current and future policies in the UK and beyond. The research is closely aligned with policies for digital land use planning such as the NPPF (MHCLG, 2021), Levelling up and digital strategies (DLUHC, 2022c; UK Government, 2022), Urban agenda for the EU (European Commission, 2023a), and no net land take policy (Decoville and Feltgen, 2023; Van Liedekerke et al., 2014). The successful implementation of this digital tool, and stakeholder-led validation, demonstrates good practice in the development of digital tools to support brownfield redevelopment and should influence future policy development around approaches to creating such tools. The tool's development-policy interaction can create feedback loops where the effectiveness of digital tools and policies are mutually enhanced within the brownfield redevelopment sector. The digital workflow used for the DSS is transferrable to other areas and contexts, subject to user requirements and data availability. Future research should build on the DSS development process and establish the wider applicability of its methods and outputs. Opportunities for further investigation that complement the scope and purpose of the DSS within the context of emerging sustainable development policies should also be explored. Overall, the research has established the value and utility of the decision support system approach in helping guide digital brownfield redevelopment planning processes.

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.2023.119145.

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