ELLIS BERNARD HAMMOND

ADVANCING THE DEVELOPMENT AND APPLICATION OF DECISION SUPPORT SYSTEMS FOR SUSTAINABLE BROWNFIELD REDEVELOPMENT

SCHOOL OF WATER, ENERGY AND ENVIRONMENT

PhD

Academic Year: 2019 – 2023

Supervisors:

Prof. Frederic Coulon, Prof. Stephen Hallett, and Dr Darren Beriro

December 2023

SCHOOL OF WATER, ENERGY AND ENVIRONMENT

PhD

Academic Year: 2019 – 2023

ELLIS BENARD HAMMOND

ADVANCING THE DEVELOPMENT AND APPLICATION OF DECISION SUPPORT SYSTEMS FOR SUSTAINABLE BROWNFIELD REDEVELOPMENT

Supervisors:

Prof. Frederic Coulon, Prof. Stephen Hallett, and Dr Darren Beriro

December 2023

© Cranfield University 2023. All rights reserved. No part of this publication may be reproduced without the written permission of the copyright owner.

ACADEMIC INTEGRITY DECLARATION

I declare that:

- the thesis submitted has been written by me alone.
- the thesis submitted has not been previously submitted to this university or any other.
- that all content, including primary and/or secondary data, is true to the best of my knowledge.
- that all quotations and references have been duly acknowledged according to the requirements of academic research.

I understand that to knowingly submit work in violation of the above statement will be considered by examiners as academic misconduct.

ABSTRACT

The redevelopment of brownfield sites is a vital part of ensuring sustainable urban development but has a range of challenges, including contamination and/or geotechnical hazards, leading to risk and cost implications. Brownfield redevelopment involves multiple stakeholders, from land use planners, land developers, and specialist consultants, to local community groups, and neighbouring residents. Understanding complex data and information can be difficult for decision-makers, which is exacerbated when communicating development scenarios and options with others. To support stakeholders, digital tools are often used, including specialised Decision Support Systems (DSSs). This PhD research investigates and contributes to the advancement of brownfield redevelopment DSSs. Existing and emerging challenges are evaluated, identifying improvement opportunities through a critical review of literature and large-scale sector-wide stakeholder consultation. A novel WebGIS-based DSS was developed in collaboration with land use planning stakeholders, applying the DSS to an area of post-industrial land within the Liverpool city region, UK. The DSS was evaluated through user testing, where improvements were identified and implemented, and verified, using a combination of empirical and user-testing methods. Overall, the approach and application of this PhD research demonstrates modern user led DSS development for brownfield applications, overcoming many of the limitations of existing work. The use of the DSS to support early-stage planning and redevelopment of brownfield land is aligned with and informs, multiple current policies for sustainable development and the use of applied digital technologies in planning and land development.

Keywords: sustainable urban development, digital tools, GIS, land use planning, stakeholder engagement, decision support tool.

This work was supported by the UK Natural Environment Research Council through the CENTA Doctoral Training Partnership [Ref: NE/S007350/1], WSP UK Ltd. and Groundsure Ltd.

ACKNOWLEDGEMENTS

Firstly, I would like to express my sincere gratitude to my supervisors, Prof. Frédéric Coulon, Prof. Stephen Hallett, and Dr Darren Beriro for their continuous support throughout my PhD research. Their guidance, knowledge, and patience has been invaluable throughout my research and the writing of this thesis. Special thanks also for the support that I received from my PhD CASE partners WSP UK Ltd, and Groundsure Ltd, with particular thanks to my CASE supervisors Prof. Russell Thomas (WSP), and Drew Hardy and Alistair Dick (Groundsure). Many thanks to the staff at the British Geological Survey (BGS) for the support they have given me. Special thanks go to my fellow PhD students at BGS, this group has been a source of friendship as well as good advice and support. I also wish to thank Cranfield University staff, student support, and management for their support in the administration and enabling of my research. I also want to think members of staff from the Liverpool City Region Combined Authority for their time and effort during stakeholder engagement activities especially, Mark Dickens, Emma Washbourn, Tracy Gordon, and Mike Newitt. I gratefully acknowledge the funding sources that made my PhD possible as part of the NERC CENTA Doctoral Training Partnership. Special thanks to the CENTA DTP management team for their support and to my fellow CENTA PhD students for their friendship, support, and good times.

I would like to thank my parents, family, and friends for their support throughout my PhD, and for always being proud of me. Last but certainly not least; I would like to thank Bethany for her unwavering love and support. You have been by my side every step of the way, especially during difficult stages. Thank you for always being there for me, I simply could not have done this without you.

TABLE OF CONTENTS

Academic integrity declaration i
Abstract ii
Acknowledgements iv
Table of contents v
List of figures ix
List of tables xii
List of abbreviations xiv
Ethical approval xvii
1 Introduction 1
1.1 Aim and objectives 4
1.2 Thesis Structure 5
1.3 References 8
2 A critical review of decision support systems for brownfield redevelopment 12
2.1 Introduction 14
2.2 Decision support systems for brownfield redevelopment 19
2.2.1 Remediation Technology Selection 20
2.2.2 Land use suitability and site prioritisation 26
2.2.2.1 Land use suitability 26
2.2.2.2 Site prioritisation 35
2.2.2.2.1 SYRIADE 35
2.2.2.2.2 TIMBRE 38
2.2.3 Land use sustainability assessment 41
2.3 Future opportunities for DSSs 43
2.3.1 Socioeconomic issues 43
2.3.2 Geographical scale versus development stage 45
2.3.3 Data, methods, and platforms 46
2.3.4 Predictive modelling 49
2.4 Conclusions 51
2.5 Author contributions 54
2.6 References 54
2.7 Appendix 67
3 Digital tools for brownfield redevelopment: Stakeholder perspectives and opportunities 73

3.1 Introduction 75
3.2 Methodology 81
3.2.1 Stakeholder Identification 81
3.2.2 Planning and preparation 82
3.2.3 Key stakeholder interviews 83
3.2.4 Online questionnaire 84
3.2.5 Analysis and interpretation 85
3.3 Results and discussion 86
3.3.1 Stakeholder identification 86
3.3.2 Initial stakeholder interviews 87
3.3.3 Online Questionnaire 89
3.3.3.1 Digitalisation 90
3.3.3.1.1 Remediation contractors 92
3.3.3.1.2 Land developers 93
3.3.3.1.3 Local Authority Planning 94
3.3.3.1.4 Consultants 94
3.3.3.1.5 Regulatory bodies 96
3.3.3.1.6 Scientific research community 96
3.3.3.2 Barriers for brownfield redevelopment 97
3.3.4 Challenges for brownfield digital tools 101
3.3.5 Opportunities across the brownfield sector 106
3.4 Conclusions 109
3.5 Author contributions 110
3.6 References 110
3.7 Appendix 119
3.7.1 Blank key stakeholder interview questions 123
3.7.2 Blank online questionnaire questions 123
4 The development of a novel decision support system for regional land use planning for brownfield land. 124
4.1 Introduction 126
4.2 Methods 129
4.2.1 DSS scope 130
4.2.2 User Defined Sites and Post-Industrial Land 135
4.2.3 Overview of the DSS modules 135

4.2.4 Module 1 - Land Use Potential 136
4.2.5 Module 2 - Ground risk 143
4.2.6 Module 3 - Economic evidence 145
4.2.6.1 Remediation costs 145
4.2.6.2 Estimated new build property sale price and land value 145
4.2.7 User interface 146
4.2.8 User testing 147
4.3 Results 148
4.3.1 Decision Support System 148
4.3.1.1 Reviewing high-level deliverability of sites 150
4.3.1.2 Assessing a site or areas potential for different end-uses 151
4.3.1.3 Investigating ground risk of a site 154
4.3.2 User testing results and feedback 155
4.4 Discussion 160
4.5 Conclusions 163
4.6 Author contributions 164
4.7 References 165
4.8 Appendix 170
4.8.1 Economic Evidence methodology 192
4.8.2 Improved user interface mock-ups 196
5 From data to decisions: Empowering brownfield redevelopment with a novel decision support system 205
5.1 Introduction 206
5.2 Methods 210
5.2.1 Overview of the DSS 210
5.2.2 Selection and evaluation of study sites 212
5.2.3 Quantitative verification of land use potential 215
5.2.4 Qualitative verification of sites using local expert knowledge 217
5.3 Results 218
5.3.1 Liverpool city region 218
5.3.2 Quantitative verification of land use potential 220
5.3.2.1 Residential land use 220
5.3.2.2 Other land use types 221

5.3.3 Qualitative verification of potential housing sites using local expert knowledge 222
5.3.4 Evaluation of post-industrial land and study sites 224
5.3.4.1 Land use potential 224
5.3.4.2 Ground risk 228
5.3.4.3 Economic evidence 229
5.3.5 St Helens local plan – housing and employment land 233
5.3.5.1 Land use potential 233
5.3.5.2 Ground risk 234
5.3.5.3 Economic evidence 235
5.4 Discussion 236
5.4.1 Evaluation and verification of the dss 236
5.4.2 Policy implications 241
5.5 Conclusions 244
5.6 Author contributions 245
5.7 References 245
6 Overall discussion and future research recommendations 253
6.1 Introduction 253
6.2 Key findings, implications, and knowledge gaps addressed 255
6.3 Recent developments from literature and private/public sector 262
6.3.1 GIS-MCDA based methods 262
6.3.2 Other GIS-based methods 265
6.3.3 Non-GIS-based brownfield decision-support research. 266
6.3.4 Brownfield stakeholder engagement research 268
6.3.5 Public/private sector developments 270
6.4 Further research recommendations 272
6.5 Limitations of the research 274
6.6 References 275

LIST OF FIGURES

Figure 1.1 Thesis structure and chapters mapped against each objective. 8
Figure 2.1 The typical planning and land development process for brownfield sites indicating the relationship between steps within each domain showing how scale, data and uncertainty reduce over time..... 15
Figure 2.2 Overview of decision-making methods used in Environmental Management DSSs. 18
Figure 2.3 MCDA hierarchy of TIMBRE, from Pizzol et al., 2016. 39
Figure 3.1 The typical planning and land development process for brownfield sites indicating the relationship between steps within each domain showing how scale, data and uncertainty reduce over time (Hammond et al., 2021). 76
Figure 3.2 Stakeholder groups identified and mapped based on their involvement in the brownfield redevelopment process. 82
Figure 3.3 Questionnaire response by stakeholder type. 90
Figure 3.4 Use and reliance on digital tools across stakeholder types. 92
Figure 3.5 A word cloud generated from the textual responses when stakeholders were asked about cost drivers for remediation and ground engineering. 98
Figure 3.6 Occurrence of keywords when stakeholders mentioned “data”. 100
Figure 4.1 User personas for the DSS use-case, digital skills range from 1 (least skilled) to 5 (highly skilled).. 134
Figure 4.2 Summary of methodology and steps taken to transform, process, and integrate data for the DSS..... 137
Figure 4.3 Overview of methodology approach for Land Use Potential outputs. 138
Figure 4.4 The user journey through the DSS. 148
Figure 4.5 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). 149
Figure 4.6 The user interface of the DSS for the summary screen.. 151
Figure 4.7 The user interface of the DSS for Land Use Potential Module showing site summary view (a), Site detailed view (b), and Land Use Potential drivers within the pop-up window (c).. 152

Figure 4.8 The user interface of the DSS for Land Use Potential Module showing Post-industrial land use Potential layer, overlain by contextual layers. 153
Figure 4.9 The user interface of the DSS for Ground Risk Module showing site detailed view for contamination risk, the linking button to supporting data window is also visible. 154
Figure 4.10 The user interface of the DSS for Ground Risk Module showing supporting data (in this case Historic Land use).. 155
Figure 4.11 Radar plots showing responses from stakeholders when asked to rank usability aspects of the DSS, scores are aggregated and averaged by stakeholder type. 158
Figure 4.12 DSS Approach. 160
Figure 4.13 Improvement mock-up showing how densities for economic evidence outputs would be adjusted in real-time within the DSS interface. 197
Figure 4.14 Improvement mock-up showing how location and zoom would be preserved when moving between DSS modules 198
Figure 4.15 Improvement mock-up showing the selection and side by side comparison of multiple sites at once 199
Figure 4.16 Improvement mock-up showing the process for how users would upload their own spatial data into the DSS in real-time 200
Figure 4.17 Improvement mock-up showing the process for uses adjusting display order and transparency of layers within the DSS interface in real-time. 201
Figure 4.18 Improvement mock-up showing the process for self-closing pop-ups 202
Figure 4.19 Improvement mock-up showing an explanatory pop-up for ground risk scores 203
Figure 4.20 Improvement mock-up showing the process of exporting results from the summary screen 204
Figure 5.1 DSS Overview, showing data layers within the three modules (Land use Potential, Ground Risk, Economic Evidence). 211
Figure 5.2 Example of site summary (a) and site detailed (b) views. 212
Figure 5.3 Liverpool city region distribution of SHLAA sites (a), post-industrial land areas (b), and St Helens local plan development areas (c, d). 213

Figure 5.4 Summary of methods for case-study application and verification of DSS outputs. 215
Figure 5.5 The Liverpool city-region and its six constituent Local Authorities. 219
Figure 5.6 Residential land use potential for LCR post-industrial land. 225
Figure 5.7 Distribution of contamination ground risk scores for post-industrial land in the Liverpool city region. 228
Figure 5.8 LCRCA post-industrial land new build house prices per m^2 overlain by the top 20% most deprived areas in LCRCA. 230
Figure 5.9 Residential land use potential assessment for St Helens Local Plan policy area 4HA**.** 233
Figure 5.10 Ground risk scores for St Helens local plan housing development area 6HA, showing (a) contamination risk, and (b) geotechnical risk. 234
Figure 5.11 Estimated land value for each site within the St Helens local plan areas for housing and employment land. 235
Figure 6.1 Schematic interrelations between the objectives (1 to 5) of the PhD research, and the overall impact on the brownfield sector. Objective 5 is split into two parts (a) verification, and (b) Recommendations for policy and future research. 254
Figure 6.2 A simplified brownfield land development process, after Hammond et al (2021). Yellow boxes demonstrate how the DSS supports decision-makers in early-stage challenges. 259

LIST OF TABLES

Table 2.1 Summary of remediation technology selection DSSs..... 21
Table 2.2 Summary of land use suitability DSSs. 28
Table 2.3 Comparison of TIMBRE and SYRIADE features..... 37
Table 2.4 Summary of research reviewed for this study. 67
Table 3.1 Stakeholder Categories. 86
Table 3.2 A ranking of key brownfield redevelopment issues as determined by stakeholders who responded to the questionnaire. 97
Table 3.3 Variability of key brownfield issues between key stakeholder groups. 105
Table 3.4 Typical stakeholder personas established from key stakeholder interviews 119
Table 3.5 All questionnaire responses. 122
Table 3.6 Summary of questionnaire respondent profiles. 122
Table 4.1 User Stories..... 132
Table 4.2 Land Use Potential criteria selected, including weightings. 140
Table 4.3 Land Use Potential categories..... 142
Table 4.4 Land Use Potential MCDA models. 170
Table 4.5 Land use potential source datasets. 180
Table 4.6 User testing results. 183
Table 4.7 DSS Improvements. 186
Table 5.1 Size and distribution of study sites and post-industrial land within the Liverpool City Region Authority. 214
Table 5.2 Sites used for land use potential verification. 216
Table 5.3 Land Use Potential categories based on outputs from the DSS..... 217
Table 5.4 Results from verification of residential land use potential GIS-MCDA models..... 220
Table 5.5. Confusion matrix of results from verification of residential land use potential GIS-MCDA model when positive outcomes are assigned to medium potential or above. 221
Table 5.6 Result from verification of other land use types. 222
Table 5.7 Results from qualitative verification of the DSS by local experts..... 223
Table 5.8 Land use potential assessment. 226
Table 5.9 Ground risk scores for the Liverpool City Region. 229

Table 5.10 Results from economic evidence module for study sites..... 232
Table 5.11 Results from economic evidence module for St Helens local plan development areas. 236

LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
BGS	British Geological Survey
BIM	Building Information Modelling
BLRF	Brownfield Land Release Fund
BOM	Brownfield Opportunity Matrix
CA	Combined Authority
CABERNET	Concerted Action on Brownfield and Economic Regeneration Network
CDBB	Centre for Digital Built Britain
CL: AIRE	Contaminated Land: Applications in Real Environments
CPRE	Campaign to Protect Rural England
DECERNS	Decision Evaluation in Complex Risk Network Systems
DESYRE	Decision Support System for The Requalification of Contaminated Sites
DLUHC	Department for Levelling Up, Homes, and Communities
DSS	Decision Support System
DST	Decision Support Tool
EA	Environment Agency
EC	European Commission
ELECTRE	Elimination and Choice Translating Reality
EU	European Union
GI	Ground Investigation
GIS	Geographical Information System
GUI	Graphical User Interface

HCA	Homes And Communities Agency
ISO	International Standards Organization
LA	Local Authority
LCR	Liverpool City Region
LCRCA	Liverpool City Region Combined Authority
LPA	Local Planning Authority
LSOA	Lower Super Output Area
LUP	Land Use Potential
MAUT	Multi-Attribute Utility Theory
MAVT	Multi-Attribute Value Theory
MCDA	Multi-Criteria Decision Analysis
MHCLG	Ministry of Housing, Communities & Local Government
NASA	National Aeronautics and Space Administration
NDTP	National Digital Twin Programme
NERC	Natural Environment Research Council
NLDP	National Land Data Programme
NPPF	National Planning Policy Framework
OPE	One Public Estate
OS	Ordnance Survey
PBL	Presence and Background Learning
PIL	Post-Industrial Land
PROMETHEE	Preference Ranking Organization Method for Enrichment of Evaluations
PSS	Planning Support System

SADA	Spatial Analysis and Decision Assistance
SCORE	Sustainable Choice of Remediation
SDG	Sustainable Development Goal
SDS	Spatial Development Strategy
SHELAA	Strategic Housing and Economic Land Availability Assessment
SHLAA	Strategic Housing Land Availability Assessment
SI	Site Investigation
Surf-UK	United Kingdom's Sustainable Remediation Forum
SYRIADE	Spatial Decision Support System for Regional Risk Assessment of Degraded Land
TIMBRE	Tailored Improvement of Brownfield Regeneration in Europe
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UI	User Interface
UK	United Kingdom
UKRI	United Kingdom Research and Innovation
UN	United Nations
UNEP	United Nations Environment Programme
US EPA	United States Environmental Protection Agency
USA	United States of America
USGS	United States Geological Survey
WMS	Web Map Service
WoE	Weight of Evidence
WSM	Weighted Sum Model

ETHICAL APPROVAL

This research was conducted with ethical approval from Cranfield University.

Reference: CURES/9386/2019

1 INTRODUCTION

Brownfield land can be defined in many ways, but in general, the term refers to sites and surrounding land that have been impacted by historical land use or industrial activity, often resulting in contamination, dereliction, and underutilisation (Alker et al., 2000; Chen et al., 2016). The size, location and nature of brownfield sites varies between countries. In Europe, brownfield sites tend to be smaller and located within urban communities, while in the USA and China, brownfield sites are often larger, complex sites located in remote locations or at the margins of cities. (Green, 2018; Liu et al., 2014; Oliver et al., 2005; US EPA, 2017). As the demand for housing and land for development has increased, interest in the potential of brownfield land has become of global importance (US EPA, 2015; European Commission, 2013; Hepburn et al., 2019). By redeveloping brownfield sites, valuable land can be reclaimed, reducing pressure on undeveloped land, and promoting sustainable development (Thornton et al., 2007; Van Liedekerke et al., 2014).

Brownfield sites offer valuable opportunities for development with many benefits including the creation of new housing options and additional ecosystem services. When properly remediated and developed, brownfield sites can help to address the housing shortage seen in many cities, by supporting the construction of high-density housing options (Chen et al., 2016). This can reduce urban sprawl and preserve green spaces on the outskirts of cities providing environmental benefits. Brownfield redevelopment can provide additional green space within urban areas, promoting human health and well-being (Bonthoux et al., 2014). Additionally, the development of *green infrastructure*, such as solar farms, or sustainable urban drainage (SuDS) can help mitigate the effects of climate change (Scholz et al., 2014; Caemmerer-Seibel et al., 2019). Decision makers can

leverage the great potential of brownfield sites to ensure sustainable urban development and provide added value to the built environment for citizens.

To redevelop brownfield sites, developers generally follow a sequential series of steps within the context of the planning and development process (see Figure 2.1). First, a thorough site investigation is conducted (usually by specialist consultants) to understand the site's condition and any identify any potential contamination (Environment Agency, 2023). Next, a feasibility study is carried out to evaluate economic, environmental, and social viability. Once the developer is satisfied, planning approval is sought from local authorities, which is often granted subject to the development meeting certain conditions (i.e., addressing environmental and/or land-use/design concerns) (MHCLG, 2021). If contamination or other ground hazards are present, remediation work is carried out (usually by a third-party remediation contractor) (Environment Agency, 2023). Alongside this, a detailed design and development plan is created by the developer, and necessary infrastructure work is undertaken to allow construction to take place. Construction then takes place, in compliance with planning conditions and safety and regulatory standards, with ongoing monitoring to ensure quality and environmental compliance. These steps may vary depending on site-specific factors and the complexity of the redevelopment project (Longo and Campbell, 2017).

Understanding the characteristics of brownfield sites in different regions is crucial for effective planning and redevelopment. However, brownfield redevelopment is a complex process that requires collaboration among multiple stakeholders to achieve sustainable development (United Nations, 2023). This complexity is increased with the inclusion of factors such as environmental constraints (i.e., contamination in soil and groundwater), social factors (i.e., opinions on development end use), and economic considerations (i.e.,

site viability) (Longo and Campbell, 2017). This unique confluence of decision making challenges can make finding an ideal solution for all stakeholders complicated, and reaching a compromise may also be difficult because of poor information acquisition (Alexandrescu et al., 2017; Cappai et al., 2019).

To address these challenges, digital tools such as Decision Support Systems (DSSs) have been developed to support stakeholders involved in brownfield site decision making. DSSs, in general, are specialised digital tools that enhance the value of data and information, improving a user's understanding of an issue or problem (Agostini and Vega, 2009; Black and Stockton, 2009) and facilitating discussion around key issues. Brownfield DSSs are often designed to be used by a wide range of stakeholders to improve decision making processes concerning the interaction of multiple factors in these post-industrial and post-use sites. DSSs often use decision analysis techniques such as Multi-Criteria Decision Analysis (MCDA) to rank and select the most suitable and viable options (Giove et al., 2008), or GIS analysis to map and visualise redevelopment options and strategies for site remediation (clean-up) (Chrysochoou et al., 2012).

While successful research and case studies have demonstrated the potential benefits of DSSs in brownfield redevelopment decision making, their regular use and implementation currently remain low (Ameller et al., 2020). Often these tools do not fully capture the complexity of situations such as brownfield redevelopment. There is a research gap for the integration of spatial planning, economic, and environmental datasets, with modern digital tools and decision making methods. Existing brownfield DSS research primarily focuses on site-specific decision making problems that arise later in the planning and development process, after detailed intrusive site investigation. The usability and accessibility of a DSS are crucial for success (Bartke et al., 2017), despite

this, stakeholder/user (e.g., land-use planners and land developers) involvement in the DSS development process is often limited in existing brownfield DSS research.

To advance this area future research should seek to address these limitations. Improvements in these areas would support stakeholders by effectively balancing environmental constraints, social factors, economic considerations, and stakeholder preferences with well-designed digital decision support leading to more sustainable brownfield planning and redevelopment outcomes.

1.1 Aim and objectives

The aim of this PhD research is 'to assess how spatial datasets can be integrated into GIS-based DSSs to better inform the decision making process and enable the sustainable reuse of brownfield land'. This aim has led to the production of a new DSS and underpinning research, with demonstrable potential to influence policy and digital planning practices. Overall, this PhD research contributes to the advancement of DSSs for brownfield redevelopment decision making, ultimately supporting sustainable development.

To achieve this stated research aim, the following objectives are addressed:

- **Objective 1:** To critically analyse the nature and state of decision support systems (DSS) for brownfield redevelopment.
- **Objective 2:** To identify the need for advancing the current state of the art through user needs assessment.
- **Objective 3:** To conceptualise and implement a novel spatial framework that enables a comprehensive assessment of brownfield sites.
- **Objective 4:** To evaluate the spatial framework using a case study application and user testing.

- **Objective 5:** To verify the DSS outputs through a combination of user testing and empirical evidence, and to provide recommendations for future scientific research and policy.

1.2 Thesis Structure

The PhD thesis is comprised of six chapters, of which four have been written in manuscript format and have been published. Figure 1.1 shows how each chapter is related to the specific objectives. A brief description of each chapter is provided:

Chapter 1: This chapter is an introduction to the thesis and includes its aim, objectives, and thesis structure.

Chapter 2: This chapter is a critical literature review of DSS research for brownfield redevelopment applications. This critical review examines research published between 1998 and 2021. The status of DSSs for brownfield redevelopment applications is summarised, highlighting the advantages and limitations of existing research along with opportunities for improvement of future DSSs.

This critical review was published in the journal *Science of the Total Environment* in April 2021 (Hammond et al., 2021) and at the time of writing had 33 academic citations (doi.org/10.1016/j.scitotenv.2021.147132).

Chapter 3: This chapter presents findings from a large-scale stakeholder consultation conducted for this PhD research. The stakeholder consultation campaign involved UK brownfield and contaminated land professionals and was conducted in 2020 and 2021. The stakeholder consultation was designed to ascertain the level of digitalisation within the UK brownfield sector. This chapter also highlights key brownfield redevelopment

issues, identifying opportunities for the development of digital tools to enhance brownfield decision making.

This work was published in the *Journal of Environmental Management* in January 2023 (Hammond et al., 2023a) and at the time of writing had 4 academic citations (doi.org/10.1016/j.jenvman.2022.116393).

Chapter 4: This chapter presents the steps taken to develop a prototype DSS aimed at providing support for early-stage, city region scale brownfield planning and redevelopment. Through user requirements gathering and the creation of a detailed use case, specific design, methods, and techniques to create the DSS outputs and user interface were established. Results from user testing and feedback on the DSS with stakeholders from the study area are presented. Feedback obtained during user testing assisted with improving the functionality, usability, and effectiveness of the DSS. Finally, findings from DSS development and user testing are discussed in the context of existing brownfield DSS research, as are implications for best practice DSS development.

This work was published in the *Journal of Environmental Management* in January 2024 (Hammond et al., 2024) (doi.org/10.1016/j.jenvman.2023.119466).

Chapter 5: This chapter presents the application of the DSS to the Liverpool City Region. The results of this application are presented and verified against real-world land use planning decision making and through user testing with case-study stakeholders. Findings from verification work and case-study application are discussed, as are the implications of this research for the use of digital tools for brownfield land use planning and brownfield planning policy in the UK and other countries.

This work was published in the *Journal of Environmental Management* in December 2023 (Hammond et al., 2023b) and at the time of writing had 1 academic citation (doi.org/10.1016/j.jenvman.2023.119145).

Chapter 6: This chapter provides an overall discussion and summary of the key outputs from each chapter. Further, it describes how each chapter contributed to the achievement of the aim and objectives of the research along with the overall implications of the PhD research.

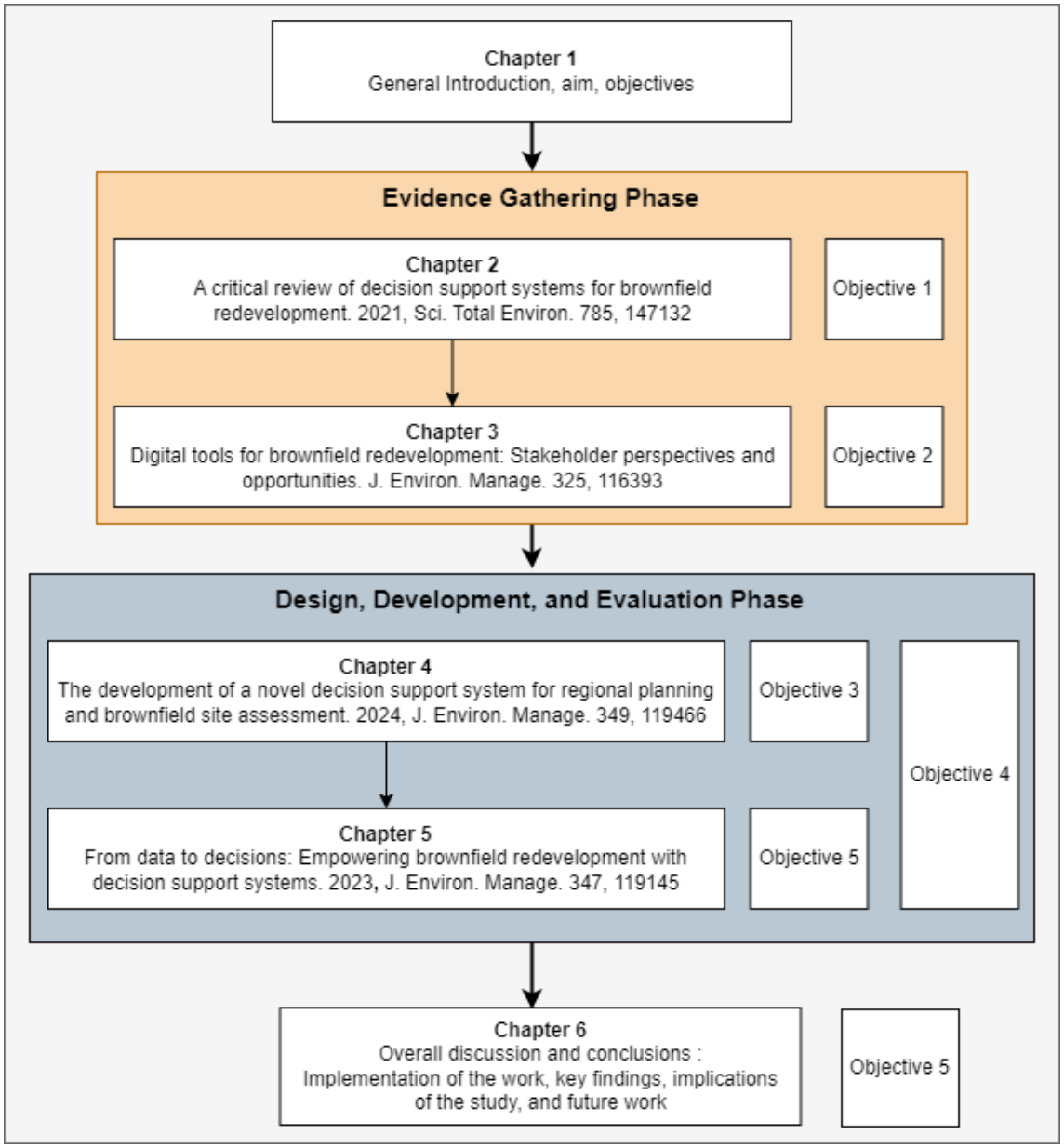


Figure 1.1 Thesis structure and chapters mapped against each objective.

1.3 References

Agostini, P., Vega, A., 2009. Decision Support Systems (DSSs) for Contaminated Land Management -- Gaps and Challenges, in: Marcomini, A., Suter II, G.W., Critto, A. (Eds.), Decision Support Systems for Risk-Based Management of Contaminated Sites. Springer US, Boston, MA, pp. 1–6. https://doi.org/10.1007/978-0-387-09722-0_13

Alexandrescu, F., Klusáček, P., Bartke, S., Osman, R., Frantál, B., Martinát, S., Kunc, J., Pizzol, L., Zabeo, A., Giubilato, E., Critto, A., Bleicher, A., 2017. Actor networks and the construction of applicable knowledge: the case of the Timbre Brownfield

Prioritization Tool. Clean Technol. Environ. Policy 19, 1323–1334. https://doi.org/10.1007/s10098-016-1331-8

Alker, S., Joy, V., Roberts, P., Smith, N., 2000. The definition of brownfield. J. Environ. Plan. Manag. 43, 49–69. https://doi.org/10.1080/09640560010766

Ameller, J., Rinaudo, J.D., Merly, C., 2020. The Contribution of Economic Science to Brownfield Redevelopment: A Review. Integr. Environ. Assess. Manag. 16, 184–196. https://doi.org/10.1002/ieam.4233

Bartke, S., Martinát, S., Klusáček, P., Pizzol, L., Alexandrescu, F., Frantál, B., Critto, A., Zabeo, A., 2016. Targeted selection of brownfields from portfolios for sustainable regeneration: User experiences from five cases testing the Timbre Brownfield Prioritization Tool. J. Environ. Manage. 184, 94–107. https://doi.org/10.1016/j.jenvman.2016.07.037

Black, P., Stockton, T., 2009. Basic Steps for the Development of Decision Support Systems, in: Marcomini, A., Suter II, G.W., Critto, A. (Eds.), Decision Support Systems for Risk-Based Management of Contaminated Sites. Springer US, Boston, MA, pp. 1–27. https://doi.org/10.1007/978-0-387-09722-0_1

Bonthoux, S., Brun, M., Di Pietro, F., Greulich, S., Bouché-Pillon, S., 2014. How can wastelands promote biodiversity in cities? A review. Landsc. Urban Plan. 132, 79-88. https://doi.org/10.1016/j.landurbplan.2014.08.01

Caemmerer-Seibel, U., Lück, A., Osman, A., Kiesel, G., Völker, C., Alfen, H.W., Cebulla, D., 2019. Energy transition in rural areas - supporting local energy planning by the development of an online tool for identification and promotion of energy efficiency and the use of renewables, in: Building Simulation Conference Proceedings. pp. 2619–2626.

Cappai, F., Forgues, D., Glaus, M., 2019. A Methodological Approach for Evaluating Brownfield Redevelopment Projects. Urban Sci. 2019, Vol. 3, Page 45 3, 45. https://doi.org/10.3390/URBANSCI3020045

Chen, I.-C., Tsai, Y.-C., Ma, H.-W., 2016. Toward sustainable brownfield redevelopment using life-cycle thinking. Sustain. 8 (10), 994 https://doi.org/10.3390/su8100994

Chilton, K., Schwarz, P., Godwin, K., 2015. Final Report: Verifying the Social, Environmental, and Economic Promise of Brownfield Programs.

Chrysochoou, M., Brown, K., Dahal, G., Granda-Carvajal, C., Segerson, K., Garrick, N., Bagtzoglou, A., 2012. A GIS and indexing scheme to screen brownfields for area-wide redevelopment planning. Landsc. Urban Plan. 105, 187–198. https://doi.org/10.1016/j.landurbplan.2011.12.010

Environment Agency, 2023. Land contamination: risk management [WWW Document]. URL https://www.gov.uk/guidance/land-contamination-how-to-manage-the-risks (accessed 29.11.23).

European Commission, 2013. Science for Environment Policy. Thematic Issue: Brownfield Regeneration.

Giove, S., Brancia, A., Satterstrom, F.K., Linkov, I., 2008. Decision Support Systems and Environment: Role of MCDA, in: Marcomini, A., Suter II, G.W., Critto, A. (Eds.), Decision Support Systems for Risk-Based Management of Contaminated Sites. Springer US, Boston, MA, pp. 1–21. https://doi.org/10.1007/978-0-387-09722-0_3

Green, T.L., 2018. Evaluating predictors for brownfield redevelopment. Land use policy 73, 299–319. https://doi.org/10.1016/j.landusepol.2018.01.008

Hammond, E.B., Coulon, F., Hallett, S.H., Thomas, R., Hardy, D., Kingdon, A., Beriro, D.J., 2021. A critical review of decision support systems for brownfield redevelopment. Sci. Total Environ. 785, 147132. https://doi.org/10.1016/j.scitotenv.2021.147132

Hammond, E.B., Coulon, F., Hallett, S.H., Thomas, R., Hardy, D., Beriro, D.J., 2023a. Digital tools for brownfield redevelopment: Stakeholder perspectives and opportunities. J. Environ. Manage. 325, 116393. https://doi.org/10.1016/J.JENVMAN.2022.116393

Hammond, E.B., Coulon, F., Hallett, S.H., Thomas, R., Dick, A., Hardy, D., Dickens, M., Washbourn, E., Beriro, D.J., 2023b. From data to decisions: Empowering brownfield redevelopment with a novel decision support system. J. Environ. Manage. 347, 119145. https://doi.org/10.1016/J.JENVMAN.2023.119145

Hammond, E.B., Coulon, F., Hallett, S.H., Thomas, R., Dick, A., Hardy, D., Dickens, M., Washbourn, E., Beriro, D.J., 2024. The development of a novel decision support system

for regional land use planning for brownfield land. J. Environ. Manage. 349, 119466. https://doi.org/10.1016/J.JENVMAN.2023.119466

Hepburn, E., Northway, A., Bekele, D., Currell, M., 2019. A framework and simple decision support tool for groundwater contamination assessment in an urban redevelopment precinct. Hydrogeol. J. 27, 1911–1928. https://doi.org/10.1007/s10040-019-01970-9

Liu, Y., van Oort, F., Geertman, S., Lin, Y., 2014. Institutional determinants of brownfield formation in Chinese cities and urban villages. Habitat Int. 44, 72–78. https://doi.org/10.1016/J.HABITATINT.2014.05.005

Longo, A., Campbell, D., 2017. The Determinants of Brownfields Redevelopment in England. Environ. Resour. Econ. 67. https://doi.org/10.1007/s10640-015-9985-y

Ministry of Housing Communities and Local Government, 2021. National Planning Policy Framework.

Oliver, L., Ferber, U., Grimski, D., Millar, K., Nathanail, P., 2005. The Scale and Nature of European Brownfields 8.

2 A CRITICAL REVIEW OF DECISION SUPPORT SYSTEMS FOR BROWNFIELD REDEVELOPMENT

Ellis B. Hammond[1, 2], Frederic Coulon[2], Stephen H. Hallett[2], Russell Thomas[3], Drew Hardy[4], Andrew Kingdon[1], Darren J. Beriro[1*].

[1]British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK.

[2]School of Water, Energy and Environment, Cranfield University, Cranfield, MK43 0AL, UK.

[3]WSP, Kings Orchard, 1 Queen St, Bristol, BS2 0HQ, UK

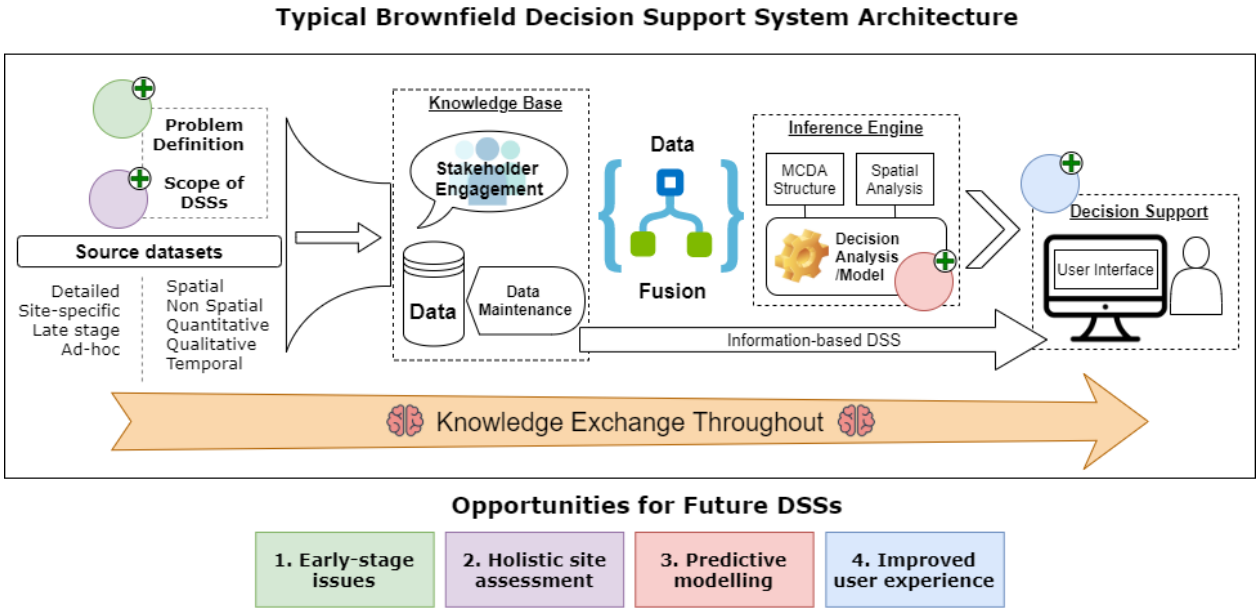
[4]Groundsure, Sovereign House, Church Street, Brighton BN1 1UJ, UK

Abstract:

Over the past two decades, many decision support systems (DSSs) have been developed to support decision makers and facilitate the planning and redevelopment process of brownfields. Existing systems are however often siloed in their approach and do not fully capture the complexity of brownfield sites from a sustainable development point of view. This critical review provides an insight into the development and implementation of DSSs, published and emerging, together with an assessment of their strengths, limitations, and opportunities for future integration. Brownfields DSS applications include remediation technology selection; land use planning; and risk assessment. The results of this review lead the authors to identify four opportunities to improve brownfield DSSs: (1) an increased use of qualitative socioeconomic criteria, particularly costs and economic variables, (2) decision support systems designed to support the early-stages of brownfield redevelopment, (3) the integration of predictive modelling methods, and (4) the improvement of user interfaces and use modern web-based functionalities.

Keywords: Decision analysis, Post-industrial land, Contaminated land, Sustainable development, Land-use planning

Graphical Abstract:



2.1 Introduction

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

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

remediation is greater than its impact, and that the optimum remediation solution is selected through the use of a balanced decision making process" (Bardos et al., 2018). The planning and development process for brownfield sites can depend on project or site-specific requirements. Figure 2.1 shows the typical planning and land development process for brownfield sites, highlighting the relationships between land use planning scale, development stage, uncertainty in decision making, and data needs.

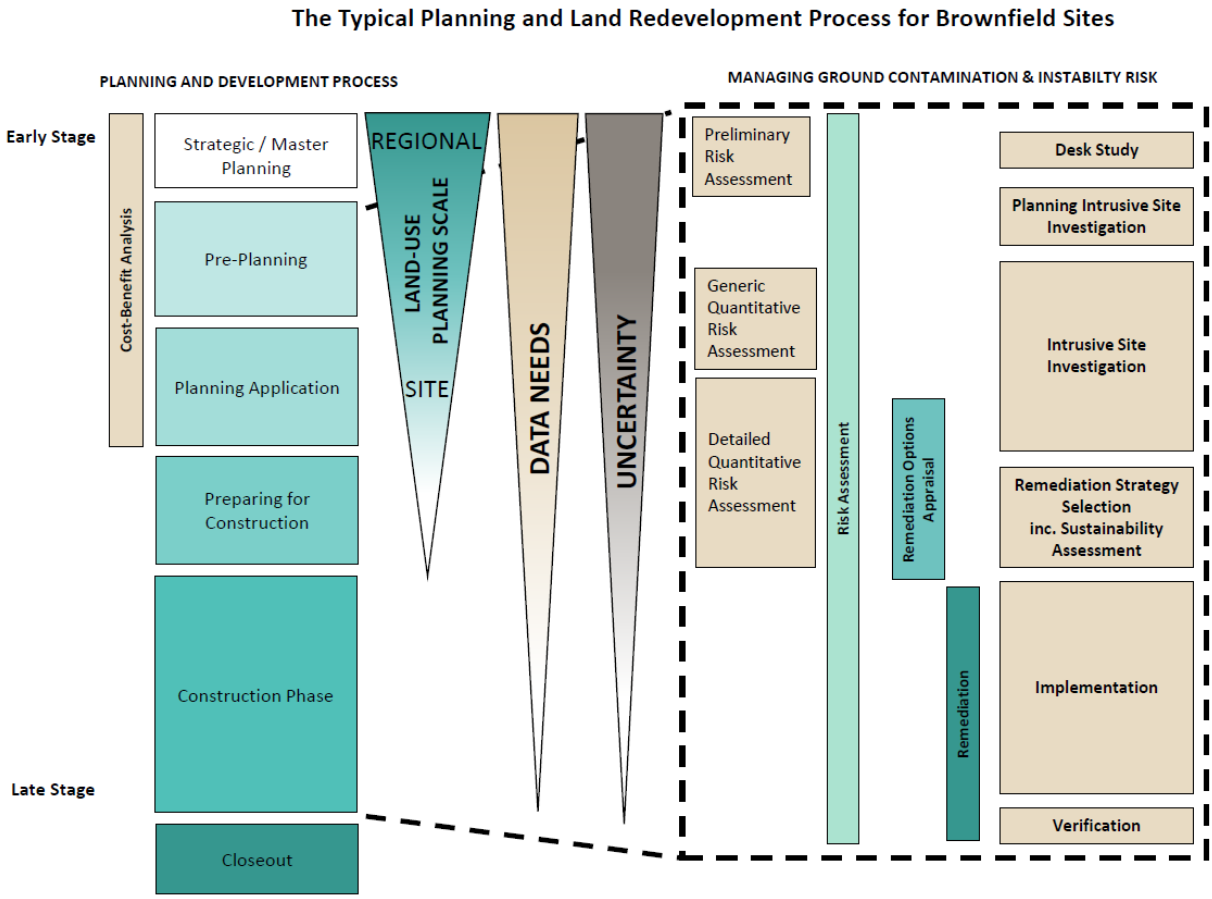


Figure 2.1 The typical planning and land development process for brownfield sites indicating the relationship between steps within each domain showing how scale, data and uncertainty reduce over time.

Decision Support Systems (DSSs) are designed to enhance the value of data, information and understanding used to inform the brownfield development processes by planners, developers, contractors, and their advisors. DSSs are classified into two main groups: (1) information-based, which presents information and may include some data analysis (e.g.

a map of interpolated concentrations of soil contamination (Ault and MacKenzie, 2006)), and (2) model-based, which typically incorporate a problem-solving element such as numerical decision analysis (Black and Stockton, 2009) (e.g. multi-criteria decision analysis (MCDA) for assessing landfill waste categorisation (Feo and De Gisi, 2014)). The range of decision making methods currently available and being used within environmental management DSSs are summarised in Figure 2.2. This review focuses solely on model-based MCDA DSSs, used to calculate, rank and sort optimum outcomes to support brownfield redevelopment. DSS method selection is dependent on the nature of the problem and the types of data and information that are being evaluated. Consequently, this means that methods are tailored to address different tasks.

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

framework to enable the examination of problems with uncertainty and non-linearity which allows for high flexibility and effectiveness in comparison to other methods as it is possible to combine several rules simultaneously (Di Nardo et al., 2019).

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

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

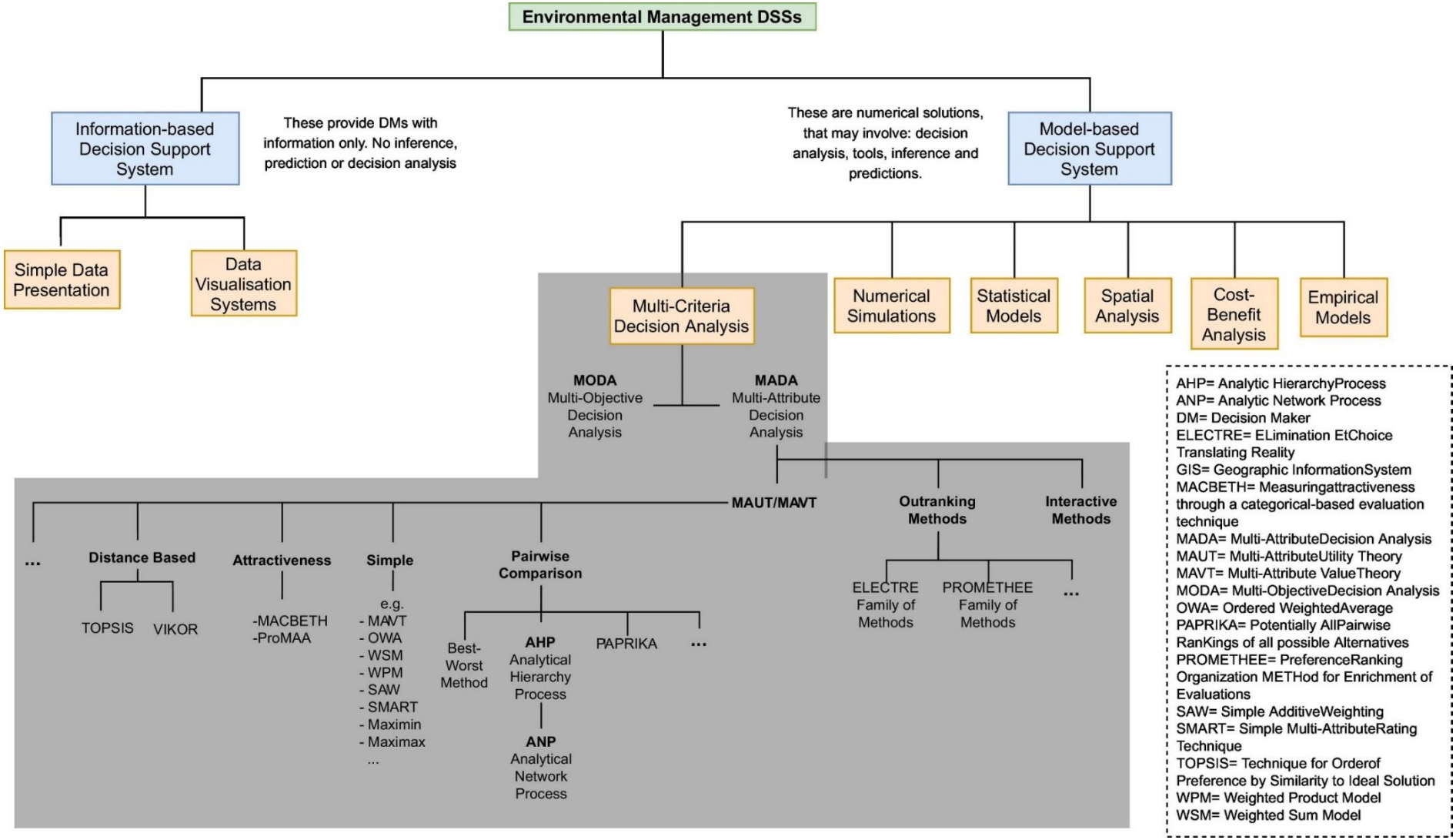


Figure 2.2 Overview of decision-making methods used in Environmental Management DSSs.

2.2 Decision support systems for brownfield redevelopment

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

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

Three main applications for brownfield DSS research were deduced from the literature: (1) the selection of remediation methods for soil and groundwater contamination (n = 15), (2) evaluation of the land use suitability, including sustainability assessment (n = 15), and

(3) ranking/indexing of sites for land use suitability (n = 8). Other applications include, ecological risk assessment, facilitating stakeholder engagement with project development, and reviews. A tabulated summary of all 54 publications is provided in Table 2.4 (Appendix 2.7).

2.2.1 Remediation Technology Selection

A summary and scope of the DSSs applied to remediation method selection are provided in Table 2.1. These DSSs are all designed to help end-users select the most appropriate remediation method for soil and groundwater contamination. Eleven of the DSSs focus on the environmental and contamination constraints on remediation method selection after site investigation and characterisation is completed. Seven of the fifteen studies utilise a single MCDA methodology, with AHP proving the most popular.

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

Table 2.1 Summary of remediation technology selection DSSs.

Author (s)	Year	DSS Name	MCDA Method	Redevelopment Stage	Environmental Criteria	Social Criteria	Economic Criteria	Other Criteria
Hokkanen *et al*.	2000	n/a	SMAA-2	Post-site characterisation	Environment	n/a	Cost Credibility of the offer	Innovation Project Management
Salt and Dunsmore	2000	n/a	Goal Programming	Post-site characterisation	Soil erosion and sedimentation, Soil organic matter, Soil nutrient transport to water, Soil pollutant transport to water, Ammonia emissions, Biodiversity, Landscape quality, Agricultural product quality, Agricultural product quantity, Animal welfare	n/a	Agricultural product quality, Agricultural product quantity	n/a
Nasiri *et al*.	2007	n/a	Fuzzy-WSM	Post-site characterisation	Contaminants Soil types	n/a	n/a	Time Durability
Promentilla *et al*.	2008	n/a	Fuzzy-ANP	Post-site characterisation	Environmental effectiveness	Social acceptability	Financial affordability	Implementability
Bello-Dambatta *et al*.	2009	n/a	AHP	Post-site characterisation	Technical efficacy Wider Environment Waste by-products	Societal Considerations	Cost-effectiveness	Regulatory obligation
Pizzol *et al*. and Critto and Agostini Carlon	2009	DESYRE	AHP (in Decision Module)	Post-site characterisation	Residual risk extension, Residual risk magnitude, Risk magnitude reduction, Technological set quality, Environmental Impact	Socioeconomic Impact	Cost	Logistical set quality Time
Purucker *et al.*	2009	SADA	n/a (GIS Analysis)	Post-site characterisation	Chemical Benchmarks Ecological Benchmarks Benchmark screens Exposure Model Risk Mapping Site Scale Volume estimates Probability maps	n/a	n/a	n/a

Author (s)	Year	DSS Name	MCDA Method	Redevelopment Stage	Environmental Criteria	Social Criteria	Economic Criteria	Other Criteria
Sorvari and Seppala	2010		MAVT	Post-site characterisation	Groundwater quality, Ecological risk, Health risks, Emissions to air, Energy consumption, Soil loss, Groundwater loss, Space use, Waste Generation, Ecological impact	Image impact	Economic impact	n/a
Yatsalo *et al*.	2012	DECERNS	MAVT, AHP, TOPSIS and PROMETHEE, MAUT, ProMAA and fuzzy criterion weightings	Post-site characterisation	Current land use Radiological data Residual risk	Improvement of psychological wellbeing Improvement of social-economic wellbeing	Cost	Local produce consumption Population densities
Rosen *et al*. Soderqvist *et al*.	2015	SCORE	SCORE	Post-site characterisation	Soil, flora and fauna, Groundwater, Surface water, Sediment, Air, Non-renewable natural resources, non-recyclable waste	Local environmental quality and amenity Cultural heritage Equity Health and safety Local participation Local acceptance	Social Profitability	n/a
Bai *et al*.	2015	n/a	AHP-TOPSIS	Post-site characterisation	Environment Impact	Acceptability	Overall cost Resources demand	Development status applicability Clean-up time
Li *et al*.	2018	n/a	Modified AHP	Post-site characterisation	Possibility of secondary contamination risk of human security Public acceptability	n/a	Equipment cost Operation Cost Detection and analysis cost	Remediation efficiency Remediation time Technological maturity
Li *et al*.	2018	n/a	AHP-PROMETHEE	Post-site characterisation	Residual risk reduction rate	Approval and acceptance	Equipment investment operational maintenance cost	Operability Remedial duration Long-term operational stability Supervision difficulty Reuse difficulty compatibility

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

Other studies have examined outliers of criteria weights in user decision logic that influence the selection of remediation methods. Examples include Li et al. (2018) who used a modified AHP for detecting outliers by including: (1) an expert competence classification, and (2) the Grubbs criterion (Grubbs, 1969), a statistical test, used to detect outliers in normally distributed data. They detected a large deviation in AHP rankings in their analyses, indicating the need to classify and weight experts' opinions carefully and appropriately. Similarly, Sorvari and Seppälä (2010) found that a reduction in the weighting of their single cost criteria (Table 2.1) did cause some of the remediation

alternatives with lower risk reduction values to be preferentially selected. This was significant as decision-makers could be unwilling to accept this cost-reducing trade-off as the primary aim of the remediation is to significantly lower or eliminate the risk posed by the contaminant (Alexandrescu et al., 2014). These two studies (Li et al., 2018; Sorvari and Seppälä, 2010) demonstrate the importance of applying pragmatic judgement when using the outputs of a DSS, and appropriately weighting criteria (cost in this case) (Table 2.1)

DSSs have also been developed to assess the sustainability of remediation methods e.g., the Sustainable Choice Of REmediation (SCORE) DSS (Rosén et al., 2015, 2013; Söderqvist et al., 2015). Remediation method selection in SCORE uses the three components of sustainable development: Environmental, Social, and Economic (Brundtland et al., 1987; UNEP, 2020). Rosén et al. (2015) defined a list of key criteria and sub-criteria to assess each component. SCORE is unique in that it gives equal weighting to social, and economic environmental criteria. However, the SCORE method requires detailed project-specific data, including chemical concentrations, which depending on the stage of redevelopment is not always available (Figure 2.1). Huysegoms and Cappuyns (2017) critically reviewed 13 DSSs (from both the private sector and the academic literature) used for assessing remediation sustainability, focusing on how they performed against six assessment measures based upon fifteen headline categories identified by the Sustainable Remediation Framework UK (Bardos et al., 2011). The findings of this current critical review agree with Huysegoms and Cappuyns (2017) in that there is a need for greater consideration of the economic and social aspects of sustainable remediation. Eleven out of thirteen of the DSS reviewed by Huysegoms and Cappuyns (2017) only partially consider economic and social criteria. Additionally, the

value of enhancing user friendly experience when manipulating input data and outputs is also recognised by Huysegoms and Cappuyns (2017). Improving the consideration of socioeconomic variables within DSS research will allow them to become adaptable for a variety of project types alongside increasing the understanding of the influence of socioeconomic constraints on brownfield redevelopment.

Only one of the DSSs reviewed was designed to focus on estimating remediation method costs. Kaufman et al. (2005) use an empirical model to estimate remediation costs for brownfield and contaminated sites. Detailed chemical concentrations and data on the volume of the contamination are needed, therefore this model can only deliver effective outputs when detailed site-characterisation studies have been carried out, which is typically later in the development process (Figure 2.1). Accurate cost estimates can be advantageous in the early stages of site development and remediation (Fraser et al., 2018) helping to counteract delays caused by unknown ground constraints (Ameller et al., 2020; Connaughton and Mbugua, 2008; Male, 2008). The value of early-stage remediation cost estimates is demonstrated by the award-winning Brownfield Ground Risk Calculator (BGR_calc) (British Geological Survey, 2019). Cost estimates for remediation of soil and groundwater contamination in this emerging tool are based on published guidance (Homes and Communities Agency, 2015).

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

this section focus on environmental and contamination issues, neglecting the socioeconomic dimension of sustainable remediation (Smith, 2019).

2.2.2 Land use suitability and site prioritisation

Twelve DSSs designed to inform future land use suitability for brownfield sites were reviewed (Table 2.2). Land use suitability DSSs are designed to support planning professionals, mostly using MCDA and GIS to enhance the value of using environmental and planning datasets. Two types of DSSs were distinguished: (1) those that seek to assign suitable land uses within and between sites and (2) those that are designed for site prioritisation. In a manner analogous to the remediation methodology selection, many of these DSSs utilise detailed, post-site investigation data/information (Table 2.1). Land use suitability is evaluated at different stages of site redevelopment including master planning and after detailed site investigation and risk assessment (Figure 2.1). The development stage dictates the data/ information required by the DSSs. As might be expected, DSSs that evaluate land use suitability, and post-site investigation, rely on such data (Table 2.2). DSSs used for strategic planning take a broader approach by accounting for a wider range of considerations including social and economic benefits during the early stages of development (Huysegoms and Cappuyns, 2017).

2.2.2.1 Land use suitability

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

provide better support to the end-user by evaluating sites holistically and taking into account other factors including social and economic considerations.

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

Table 2.2 Summary of land use suitability DSSs.

Authors (s)	Year	Spatial DSS	Methods	Redevelopment Stage	Environmental Criteria	Social Criteria	Economic Criteria	Other Criteria
Chen *et al.*	2009	No	Dominance-Based rough set approach	Post-site characterisation		Jobs created during redevelopment	Conservative estimate tax revenue, tax gained, Optimistic estimate tax revenue, tax gained, actual tax revenue, tax gained	Number of redeveloped brownfield sites, Area of redeveloped brownfield sites, Number of in-progress brownfield sites, Area of in-progress brownfield sites
Chen *et al.*	2011	Yes	GIS ordered weighted average, AHP	Post-site characterisation	Goaf collapse Karst collapse Earthquake	Access to public transportation		Site Type
Mosadeghi *et al.*	2015	Yes	AHP, Fuzzy-AHP	Planning stage	Avoid proximity to valuable ecosystems, Floodplain areas, Fire hazard areas, Storm surge, Accessibility to the broadwater, Proximity to waterways and water bodies, Proximity to natural protected areas	Avoid scenic routes	Proximity to one of the existing growth corridors, Proximity to retail and commercial areas, avoid proximity to industrial development, avoid good quality agriculture land, Avoid intact key resource areas	Power Supply, Access to road network, Access to haulage routes, Water supply, Reliability of water resource, Sewerage, Proximity to existing marine precincts, avoid urban (residential areas), Sewerage pump out facilities
Liu *et al.*	2019	Yes	Presence-and-background learning (PBL)	Planning stage	Elevation, Slope, Former land use type, Size of land parcel, Plot ratio	Medical facility density, educational facility density, Recreational facility density, Restaurant density, Shopping facility density, Government agency density, financial	Property value, Land Value	Building stories, Architectural structure, Building age, Road accessibility, Peak time population, Population per hour in a weekday, Population per hour in a weekend,

Authors (s)	Year	Spatial DSS	Methods	Redevelopment Stage	Environmental Criteria	Social Criteria	Economic Criteria	Other Criteria
						services density, Enterprise density, Distance to district centre, Distance to park/open space, Distance to water area/ coastline		Peak time population density
Culshaw *et al.*	2006	Yes	GIS analysis	Planning stage	Groundwater protection, Flood risk, Drainage, Land contamination, Proximity to landfill, Biodiversity	Natural and Man-made heritage		
Herbst and Herbst	2006	Yes	GIS analysis	Planning stage	Size, Located in wildlife deficiency area, Importance for greenspace network, Surface Sealing, Water Features	Population density, Access from schools access from bike paths		Accessibility, Penetrability, Safety, Diversity of structures, Diversity of successional stages
Abdullahi and Pradhan	2015	Yes	GIS, Weights of Evidence	Planning stage	Distance from agricultural fields, Soil and geology properties, Distance from flood zones	Proximity to public transportation facilities, Proximity to recreation facilities, Proximity to community facilities, Population density, Residential density		Proximity to infrastructure, Proximity to road networks, Proximity to same land use types, built up density, Land use diversity
Beames *et al.*	2018	Yes	GIS analysis	Planning stage		Travel Distance to Doctors, Travel Distance to Pharmacies, Travel Distance to Employment, Travel Distance to Schools, Travel Distance to Green Spaces, Travel Distance to		

Authors (s)	Year	Spatial DSS	Methods	Redevelopment Stage	Environmental Criteria	Social Criteria	Economic Criteria	Other Criteria
						Meeting Places, Travel Distance to Shops		
Burinskiene *et al.*	2017	Yes	GIS, AHP	Post-site characterisation	Soil contamination, Heavy industry pollution, green areas, Transport pollution	The level of unemployment, The level of poverty, Household incomes, The level of public crimes, Access to educational institutions	Infrastructure investment, Cost for new real estate, Number of projects funded by EU, Number of workspaces	Empty sites, Number of schools, State and average age of new constructions, Magnitude of new constructions, Distance to the city centre
Schadler *et al.* Morio *et al.*	2011, 2012 2013	Yes	Bespoke assessment algorithms	Post-site characterisation	Contaminated area requiring soil remediation, Contaminant concentration matrix for soil, Contaminant concentration matrix for groundwater, Conflict matrix for soil contaminants, Conflict matrix for groundwater contaminants, Contaminated area requiring soil remediation, Contaminant concentration matrix for soil, Contaminant concentration matrix for groundwater, Conflict matrix for soil contaminants, Conflict matrix for	Residential areas in the surrounding area, Green spaces in the surrounding area, Local supplies within walking distance, Neighbouring uses are strongly pollution emitting, Direct vicinity to nature reserve, Low capacity of access roads, Good access to public transport, Access to clearway Good accessibility for bikers, Local amenities in walking distance, Primary school in walking distance, Great impact on recreational areas,	Suitability matrix, Suitability value, Reference land value vector, Indices for planning unit, x-value, y-value, contaminant, and land use, Land value matrix, Remaining land value matrix, Maximum land value vector, Difference to remaining land value, Remediation cost matrix, Site preparation cost vector, Site suitable for innovative industries, Adjacent enterprises w/ precarious sense of security	Planning unit area vector, Number of land use types considered, Number of planning units, Location quality matrix, Land use matrix, Number of raster rows, Number of raster columns, Neighbouring uses sensitive to emissions, good supply, and disposal infrastructure

Authors (s)	Year	Spatial DSS	Methods	Redevelopment Stage	Environmental Criteria	Social Criteria	Economic Criteria	Other Criteria
					groundwater contaminants, Total number of contaminants considered, Number of contaminants in soil considered, Compliance criteria matrix soil contaminants, Compliance criteria matrix groundwater contaminants, Number of contaminants in groundwater considered, Contaminated soil volume requiring remediation, Site contains <40% sealed soil, Site location within urban area, Site is part of a local habitat, High value tree or plant populations, Site strongly contaminated	Historically relevant buildings, Great influence on cityscape		
Odii *et al.*	2019	No	WeValue Stakeholder Engagement	Post-site characterisation	Air Emission Soil & Ground Conditions Groundwater & Surface Water Ecology Natural Resources & Waste	Human Health & Safety Ethics & Equality, Neighbourhood & Locality Communities & Community Involvement Compliance,	Direct Economic Costs & Benefits, Indirect Economic Costs & Benefits, Employment & Employment, Capital Induced Economic, Costs & Benefits, Project	

Authors (s)	Year	Spatial DSS	Methods	Redevelopment Stage	Environmental Criteria	Social Criteria	Economic Criteria	Other Criteria
						Uncertainty & Evidence Air	Lifespan & Flexibility	
Bardos *et al.*	2016	No	Brownfield Opportunity Matrix	Planning Stage	n/a	n/a	n/a	n/a

Socioeconomic assessment criteria are more commonly used in land use planning DSSs (Table 2.2) than in other applications. However, the uncertainty of these criteria weighting, and decision analysis methods is generally greater because of their subjectivity (Agostini et al., 2009). To deal with uncertainty, some land use planning DSSs use MCDA methodologies integrated with fuzzy/rough set mathematical operators. For example, Chen et al. (2011) demonstrated that using a GIS-based Ordered Weighted Average (OWA) method together with an AHP pairwise comparison produced land use classifications that can inform effective land use planning decisions. Similarly, Mosadeghi et al. (2015) developed land use classifications using both AHP and Fuzzy-AHP spatial MCDA methods to the same end. The findings of Mosadeghi et al. (2015) confirmed the findings of Kordi and Brandt (2012) that Fuzzy AHP is less sensitive to criteria weight changes. This adds credibility and weight to decision making because it addresses uncertainties associated with weighting input parameters and their role in influencing the outputs.

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

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

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

the stakeholders used to define a shortlist of criteria were recruited from one local authority area (Vilnius, Lithuania). Further research is needed to effectively evaluate and incorporate stakeholder involvement into brownfield land use planning DSSs.

2.2.2.2 Site prioritisation

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

Two key tools for the ranking of brownfield sites are reviewed below, the SYRIADE DSS and the TIMBRE Brownfield Prioritisation Tool. These were selected as they are recognised as influential DSS projects within the brownfield development literature. Table 2.3 presents a comparison of key features of TIMBRE and SYRIADE.

2.2.2.2.1 SYRIADE

The Spatial decision support SYstem for Regional rIsk Assessment of DEgraded land (SYRIADE) (Agostini et al., 2012; Pizzol et al., 2011; Zabeo et al., 2011) combines a vulnerability assessment with a ‘regional risk estimation’ for every site within a portfolio, in order to generate a risk score for the explicit purpose of ranking contaminated sites (Agostini et al., 2012; Pizzol et al., 2011; Zabeo et al., 2011). The risk score produced is based on the commonly used ‘Source-Pathway-Receptor’ or S-P-R model. This is a

product of three expert weighted variables: (1) hazard score for the source of contamination, incorporating an understanding of toxicity, (2) scores that parameterise the contaminant exposure pathways, and (3) vulnerability scores for the receptor. This approach of assigning scores to sources, pathways and receptors is similar to the emerging UK-based DSS *Brownfield Ground Risk Calculator* (British Geological Survey, 2020). Zabeo et al. (2011) present a vulnerability assessment for: human health, groundwater, protected areas, and surface water; where each is assessed against several attributes with each being assigned a score. Using a linear weighted average MCDA method, the receptor vulnerability for an area can be assigned aggregating scores. These scores are then calculated using an attribute specific spatial aggregation function in GIS software. The scores are then used in the subsequent risk assessment module of SYRIADE (Pizzol et al., 2011) which presents a unique approach to integrating a conceptual site model into a decision support system within a GIS environment.

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

Table 2.3 Comparison of TIMBRE and SYRIADE features.

DSS	Spatial DSS	Methods Used	Types of output data	Redevelopment Stage	Environmental criteria	Economic criteria	Social criteria	Temporal Analysis	Uncertainty Analysis	User friendliness	Stakeholder Involvement
SYRIADE	Yes	MCDA (Multi-Attribute Value Theory) Bespoke risk estimation equation	Fixed -Recovery potential score, R_NUT risk score, Integrated management class, Spatial representation (Maps)	Planning Stage	11	2	3	No	No	Poor user interface	Yes – small amount of stakeholder analysis
TIMBRE	Yes	MCDA (Ordered Weighted Average, Convex Combination)	User dependent - Tabulated scores, Spatial representation (Maps)	Planning Stage	5*	9*	8*	No	No	Poor user interface	Yes – comprehensive stakeholder analysis
*TIMBRE criteria quantified here are from Pizzol *et al.* (2016) case study used to illustrate typical TIMBRE criteria for brownfield projects.											

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

2.2.2.2.2 TIMBRE

Pizzol et al. (2016) present the Tailored IMprovement of Brownfield Regeneration in Europe (TIMBRE) Brownfield Prioritisation Tool. This web-based modular spatial DSS was designed to rank a portfolio of brownfield sites based on user-defined and user-weighted inputs. Inputs were categorised into dimensions (e.g., social) formed of factors (e.g., transport links) and indicators (criteria) (e.g., proximity to metro stations). Collectively these parameters were then weighted by the user. Normalisation and aggregation of these components by means of convex combination (CC) (to create a weighted average) was conducted, with the MCDA methodology *Ordered Weight Average* (OWA) method being used to generate a final score for each site. Figure 2.3

taken from Pizzol et al. (2016) shows the hierarchical structure of TIMBRE's MCDA ranking methodology.

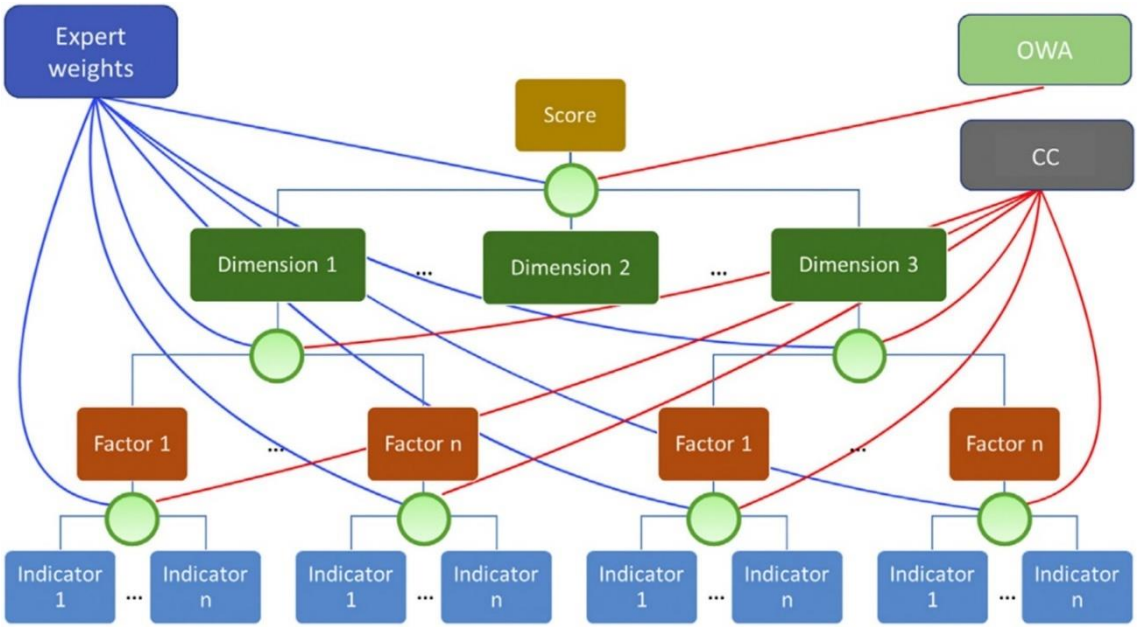


Figure 2.3 MCDA hierarchy of TIMBRE, from Pizzol et al., 2016.

TIMBRE is applied to a pilot case study area in the Czech Republic and used to rank a selection of brownfield sites for redevelopment as either a shopping centre or a solar power plant. In this example, three dimensions with sub-factors comprised of multiple indicators were defined. The three dimensions used were: (1) local redevelopment potential, (2) site-attractiveness and marketability, and (3) environmental risk. TIMBRE is designed with these three top-level criteria as default, but they can be overridden if desired. Weightings for all dimensions, factors and indicators were determined using user input. The advantage of the TIMBRE approach is that the scale and complexity of the assessment and ranking is determined by the user/ stakeholders. This means it is flexible and can be iteratively applied to a range of brownfield decision making problems (Bartke et al., 2016) to suit local context based on expert judgement and availability of information. The TIMBRE tool is evaluated in terms of usability and added value for

decision makers by Bartke et al. (2016) based on feedback from users. Their evaluation is summarised using the SWOT framework (Madsen, 2016) for user feedback, and evaluated against sustainability principles for DSSs (Bartke and Schwarze, 2015). One key shortcoming of TIMBRE is the objectivity of the results of the tool (Bartke et al., 2016; Rizzo et al., 2018). Bartke et al. (2016) state that to overcome this, clear communication of weightings and evaluation dimensions is needed between internal expert users, stakeholders, and end-users. Two other shortcomings of TIMBRE are the insufficient attention and detail around contamination issues in that there is no built-in mechanism to assess contamination, and the interoperability of TIMBRE with other software applications needs to be addressed (Bartke et al., 2016).

Features of TIMBRE and SYRAIDE are compared in Table 2.3. Each DSS achieves an effective site ranking for decision-makers to use, however, they achieve it in two different ways. SYRIADE provides a detailed assessment of sites, including regional risk assessment and vulnerability assessment, considering a variety of factors that are typically fixed. SYRIADE users can, however, add additional factors or modify proposed factors, as long as they identify the related classes the factors belong to. On the other hand, TIMBRE is a very open DSS, while the assessment framework is fixed, the assessment criteria are user dependent. Neither option is necessarily better than the other as there are advantages and disadvantages to both. On the one hand, having a rigid highly detailed DSS, like SYRIADE, can provide stakeholders with answers to specific questions, but only those questions. Whereas a more open DSS, like TIMBRE, can help to solve more dynamic problems but requires the users to fully understand the question and its component parts to produce high-quality, reliable outputs (Bartke et al., 2016; Rizzo et al., 2018).

2.2.3 Land use sustainability assessment

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

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

concerned with the monetisation of developed land, supporting earlier discussion on the benefits of varied land use types for brownfield sites.

The methodology of both Bardos et al. (2016) and Odii et al. (2019) demonstrate good practice in the conduct and implementation of stakeholder analysis for the creation of brownfield DSSs. They could be used as a framework for the inclusion of stakeholder preferences in future holistic DSSs that assess not only stakeholder perceptions and needs but also key environmental and contamination risks which are balanced with economic factors.

Bartke and Schwarze (2015) presented a review and general commentary on the quality of sustainability assessment (SA) DSSs when applied to brownfield land use planning. They examined the trade-offs between a DSS's ability to account for sustainability principles and their effectiveness in decision making. They used a set of assessment criteria established during a workshop: objectivity, transparency, practicability, participation needs [to be able to use the DSS], flexibility, and [the ease of] institutional embedding. User requirement assessment criteria were weighted against three typical user groups: the public, expert consultants, and decision makers. They reviewed three SA DSSs: RESCUE (RESCUE, 2004), SINBRA SAT (Bittens et al., 2008), and the Soil Value Balance (SVB) decision support model (Doetsch et al., 1998). They concluded that each tool reflected a different strength for the assessment criteria of the Bellagio Sustainability Assessment and Measurement Principles (BellagioSTAMP) (Pintér et al., 2012). The SVB model was shown to be the best-rounded tool, RESCUE being strongest for participation, and SINBRA SAT allows for the greatest flexibility and practicability. Bartke and Schwarze's (2015) research again highlighted the need for detailed stakeholder

and user group analysis prior to the development of DSSs. Their findings suggest that there is no ‘perfect tool’, and that trade-offs should be fully understood by users when applying these tools. None of the tools assessed scored highly for institutional embedding (ease of adoption by an institution) for any of the user groups. This suggests that to truly meet a user’s needs, a tool should be designed, or at least be able to be amended, on a case-by-case basis.

2.3 Future opportunities for DSSs

In this review, we have presented a large amount of information on DSSs to synthesise current progress and developments in decision support systems for brownfield redevelopment applications. To date, there are several types of DSSs addressing a variety of issues including remediation technology selection, land use planning and sustainability. The strengths and limitations identified in the literature have been discussed in Section 2.2 and are used to inform key points of discussion in the following sub-sections. These key considerations have informed the current authors' future research and development needs for DSS.

2.3.1 Socioeconomic issues

Socioeconomic considerations (i.e. local community building, deprivation, local amenity links) are underrepresented in the brownfield DSS reviewed. The focus of the majority of site characterisation, remediation, and land use suitability DSSs is on the environmental and contamination components of redevelopment. Socioeconomic aspects are mainly considered in DSSs designed to evaluate the overall sustainability of remediation and development schemes, accounting for all three dimensions of sustainability (social, economic, and environmental). This is also true for DSSs designed to evaluate the

sustainability of land use decision making from a socioeconomic and stakeholder point of view (Bardos et al., 2016; Odii et al., 2019).

The need for greater consideration of social and economic dimensions in DSSs for brownfield redevelopment is acknowledged by a range of authors including Bardos et al. (2016), Beames et al. (2018), Green, 2018, Huysegoms et al. (2019) and Huysegoms and Cappuyns (2017). The absence of sustainability considerations in DSSs designed for risk-based mitigation of contamination issues is likely to be because issues of this type often pose an immediate risk to receptors and the reduction of these risks (Bardos et al., 2011). Consideration of socioeconomic issues is more prominent in recent DSSs (Bai et al., 2015; Beames et al., 2018; Odii et al., 2019; Rosén et al., 2015; Tendero and Plottu, 2019; Zhu et al., 2015). However, as discussed by Huysegoms and Cappuyns (2017) these still underappreciate some socioeconomic factors, in particular detailed analysis of economic factors (Ameller et al., 2020). This is supported by the findings of this review where only one of the articles reviewed (Kaufman et al., 2005) focused specifically on developing cost estimates for brownfield site remediation. A criticism that can be made of many other DSS research incorporating economic factors is their lack of detail in their generation of economic appraisal information or simply attributing it to expert valuation. The need for better integration of economic considerations into brownfield research is also recognised by a recent review paper (Ameller et al., 2020) that further highlights that there is significant scope for improvement. The current authors suggest that the dedicated investigation of the influence and role of socioeconomic/economic factors in brownfield redevelopment be an area of future DSS research to provide a more balanced approach to decision making.

2.3.2 Geographical scale versus development stage

Most of the research reviewed focuses on site-specific brownfield decision making problems later in the planning and development process (i.e., post-detailed intrusive site investigation and remediation technology selection) (Fig. 1). As discussed in Section 2, the most common application for DSS to address is the selection of site-specific remediation technology, only sometimes is this simultaneously carried out for multiple sites (Van Der Perk et al., 2001). DSSs for selecting site-specific remediation options are dependent on detailed site-specific data and information (i.e. extent of contamination), usually acquired during the intermediate or late stages of a specific project. DSSs focusing on land use planning applications are typically for a range of scales and stages of development, but still predominantly local scale and late stage. The trend for DSSs to address late-stage site-specific problems makes sense; the functionality of DSS is better supported, with detailed data about site(s) (Black and Stockton, 2009). However, this is somewhat of a paradox. Uncertainty and unknowns regarding ground conditions typically decrease further along the investigation/development process (Figure 2.1), so it stands to reason that useful decision support tools could be more impactful in supporting decision makers during strategic/master planning or project cost-benefit evaluations.

A DSS has the capacity to aid the screening and assessment of sites, but not without challenges. At the preliminary risk assessment/ initial desk study phase of a project (Figure 2.1), a contaminated land specialist will draw together multiple sources of information, from a combination of publicly and privately held resources. This can generally be purchased as a data bundle from a commercial data reseller. A DSS has the possibility of automating this process, reducing the time to complete such studies. This could be highly beneficial in time critical due diligence projects, which often require the

assessment of vast amounts of information in a short period of time and within the early stages of planning and development, where screening the suitability of a portfolio of sites could enhance the quality, transparency and timeliness of development plan-making and decision making.

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

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

2.3.3 Data, methods, and platforms

A well-designed graphical user interface (GUI) is needed to communicate the data and information produced by a DSS to users and stakeholders (Huysegoms and Cappuyns, 2017). Two of the DSSs reviewed here developed bespoke GUIs specific to their DSS (Pizzol et al., 2016; Schädler et al., 2013). These user interfaces are quite simple and functionally similar to a standard GIS viewer, allowing users to see calculated and

mapped outputs as single or multiple attribute layers with limited interactivity. User feedback from the TIMBRE project highlighted the need for better interoperability of the DSS with commonly used software (e.g., GIS) (Bartke and Schwarze, 2015). This would mean that the DSS outputs and datasets are derived in a way that they mean they are interoperable with other software environments. Users also requested better data interrogation tools, able to view attributes and inner functions of the model (Bartke et al., 2016). These remarks are also mirrored in suggested improvements for the SYRIADE DSS (Agostini et al., 2012), whereby a GUI hosted on a web-based platform could have improved stakeholder analysis and engagement.

WebGIS (e.g., customised Google Maps) is now commonplace in today's world, with most people in developed economies using it every day in one form or another for maps or navigation purposes (Peterle, 2018). The use of WebGIS viewers as GUIs and stakeholder communication tools is recognised in literature across disciplines (Culshaw et al., 2006; Horigan et al., 2018; Kong et al., 2015; Limasset et al., 2017; Yatsalo et al., 2012). However, WebGIS viewers are rarely fully integrated into DSS for brownfield applications. Over the past decade, advances in the functionality and usability of Web-Based GIS (e.g., ESRI's ArcGIS Online) allow a larger range of geoprocessing tools to be available to the user as a complement or substitute to desktop GIS software (Kong et al., 2015; Kunapo et al., 2005; Peterle, 2018). This also means that users can access the GIS without proprietary software constraints (e.g., Leaflet – a JavaScript library for interactive maps). Furthermore, powerful visualization tools for spatial data are now becoming widely adopted by the geospatial community e.g., ESRI's ArcGIS StoryMaps (ESRI, 2020). These tools allow map viewers to be embedded in scrolling webpages, allowing the presentation of spatial data alongside explanatory text and a variety of other

media to create a user-friendly narrative. Features such as these should be used to full advantage, enabling better communication of DSS outputs and engagement of end-users. If integrated into brownfield DSS, these advances allow for the distribution of information to multiple types of non-technical stakeholders, leading to increased interaction with the data and subsequent understanding.

In the past few years, significant amounts of environmental and spatial data have been opened up in the UK, primarily from the Environment Agency (and regional equivalents) and Ordnance Survey. Open data releases and the rise of open-source GIS programs such as QGIS now mean that basic spatial data analysis can be carried out by anyone with an interest to access it rather than being limited to those with the financial means to do so. However, as it stands, an individual or organisation cannot freely and easily access the commonly agreed baseline data for brownfield desktop information (i.e., historical land use, pollution incidents) which is necessary for any robust decision support tool. In the UK, the establishment and ongoing actions of the Geospatial Commission may be a catalyst for increased uptake and use of spatial data. Furthermore, key parts of data to inform DSSs such as historical land use, are only held by private companies and hence are unlikely to ever be available as open data. The implication is that DSSs are going to need to rely on both commercial and open sources of data. It is important to make the distinction between the availability of data for viewing, e.g., Web Map Services (WMS), and the ability to engage in meaningful analysis e.g., Web Feature Services or desktop data. There are several view-only data services available for environmental data, but unless they have suitable metadata and functionality for analysis built in by the data owner, a user is unable to curate and create their analysis and DSSs. Existing available open data can also be subject to several reliability issues, including differences in

resolution, coverage, accuracy, or a combination of these (Al-Sehrawy and Kumar, 2021; Vancauwenberghe and van Loenen, 2018). This can make the normalisation of different datasets within a common tool difficult. Users and DSS developers should consider and understand the limitations of open data and data infrastructure before utilising them within their DSSs.

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

2.3.4 Predictive modelling

Only one of the DSSs reviewed applied predictive modelling techniques in their DSS (Liu et al., 2019). The machine learning technique Presence and Background Learning was used to model optimum land use designations based on human population dynamics. Many DSS within the soil and groundwater sector are already using machine learning and predictive modelling methods successfully (El Bilali et al., 2021; Fathizad et al., 2020). The apparent lack of predictive modelling, including machine learning, within brownfield DSS research is surprising given modern computing capabilities, as well as the accessibility and ease of applying predictive modelling and machine learning algorithms (Kuhn and Johnson, 2013; Pollard et al., 2019). Predictive modelling and machine learning are already commonplace in several sectors including economics and finance, medical research, and engineering. Some example applications include image classification, forecasting stock prices, simulating recovery rates in patients, and

modelling fluid dynamic systems (Kuhn and Johnson, 2013). Recent publications in contaminated land research do indicate the uptake of machine learning methods (Cipullo et al., 2019; Rodriguez-Galiano et al., 2018; Sajedi-Hosseini et al., 2018; Wu et al., 2013). Predictive modelling is also commonplace within other areas of environmental spatial analysis, such as assessing the environmental impacts of herbicides (Kurina et al., 2019). However, brownfield decision-support research is so far missing the opportunity to utilise these innovations. Powerful prediction and forecasting algorithms could be used to address issues of future land use, population, and environmental change, as well as migration of contaminants, site characteristics, or development costs. Data generated in remediation projects is often confidential, and not able to be shared for research purposes. Until this is overcome, the use of machine learning for remediation cost prediction may be difficult because obtaining sufficient data of sufficient quality is key to training and validating the models to make reliable predictions of remediation techniques and economics (Kuhn and Johnson, 2013).

To increase confidence in predictive model outputs, uncertainties should be quantified. Sensitivity analysis describes how model inputs contribute to model outputs and can provide a powerful approach by helping to understand if the model is consistent with the conceptual ground conditions it is designed to reflect. Sensitivity analysis was not commonly reported in brownfield DSS literature, only two studies were found in this review (Mosadeghi et al., 2015; Promentilla et al., 2008). Both use sensitivity analysis to show that, in comparison to other MCDA methods, fuzzy-MCDA outputs are less susceptible to undesirable changes when input variable weightings are changed. The absence of predictive models and associated sensitivity analysis in the brownfield DSS literature reviewed is again surprising given its use in wider geoscience e.g., hydrologic,

volcanic, and geomorphic modelling applications (Cannavó, 2012; Jefferson et al., 2015; Tucker and Whipple, 2002). To this end, the use of predictive models in brownfield DSSs may be a beneficial approach to constraining specific aspects of complex problems, such as changes in contamination over time or remediation cost estimates. However, any such approach should be combined with sensitivity analysis to maximise the likelihood of reliable and rational outputs.

Here we suggest the investigation of predictive modelling including machine learning methods as a key opportunity for future decision support research for brownfield redevelopment. Such advances will see improved understanding of uncertainty, new insights, and faster analysis. These benefits have the potential to improve decision making from environmental modelling, business analysis and planning standpoints.

2.4 Conclusions

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

late-stage redevelopment issues (such as remediation technology selection), (3) poor user interface and user experience within DSSs, and (4) low uptake of predictive modelling methods.

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

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

Limitations of this review: It should be noted that this review is limited to those DSSs reported in the academic literature between 1998 and 2021. Many more applications are

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

2.5 Author contributions

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

2.6 References

Abdullahi, S., Pradhan, B., 2016. Sustainable brownfields land use change modelling using GIS-based weights-of-evidence approach. Appl. Spat. Anal. Policy 9, 21–38. https:// doi.org/10.1007/s12061-015-9139-1.

Agostini, P., Critto, A., Semenzin, E., Marcomini, A., Marcomini, A., Suter II, G.W., Critto, A., 2009. Decision support systems for contaminated land management: a review. Decision Support Systems for Risk-based Management of Contaminated Sites. Springer US, Boston, MA, pp. 1–20 https://doi.org/10.1007/978-0-387-09722-0_7.

Agostini, P., Pizzol, L., Critto, A., D'Alessandro, M., Zabeo, A., Marcomini, A., 2012. Regional risk assessment for contaminated site's part 3: spatial decision support system. Environ. Int. 48, 121–132. https://doi.org/10.1016/j.envint.2012.07.005.

Alexandrescu, F., Martinát, S., Klusácek, P., Bartke, S., 2014. The path from passivity toward entrepreneurship: public sector actors in brownfield regeneration processes in Central and Eastern Europe. Organ. Environ. 27, 181–201. https://doi.org/ 10.1177/1086026614529436.

Al-Sehrawy, R., Kumar, B., 2021. Digital twins in architecture, engineering, construction and operations. A brief review and analysis. In: Toledo Santos, E., Scheer, S. (Eds.), Proceedings of the 18th International Conference on Computing in Civil and Building Engineering. Springer International Publishing, Cham, pp. 924–939.

Ameller, J., Rinaudo, J.D., Merly, C., 2020. The contribution of economic science to brownfield redevelopment: a review. Integr. Environ. Assess. Manag. 16, 184–196. https:// doi.org/10.1002/ieam.4233.

Ault, L., MacKenzie, A.C., 2006. From LIMS to Geochemistry Database: GBASE Samples Analytical Data.

Bai, L., Luo, Y., Shi, D., Xie, X., Liu, L., Zhou, Y., Yan, Z., Li, F., 2015. TOPSIS-based screening method of soil remediation technology for contaminated sites and its application. Soil Sediment Contam. 24, 386–397. https://doi.org/10.1080/15320383.2015.968915.

Bardos, P., Lewis, A., Nortcliff, S., Mariotti, C., Marot, F., Sullivan, T., 2003. Review of Decision Support Tools and their Use in Europe, a Report From the Contaminated Land Rehabilitation Network for Environmental Technologies (CLARINET) by the Decision Support Tools Working Group. Federal Environmental Agency. Vienna, Vienna (AT).

Bardos, R.P., Bone, B., Boyle, R., Harries, N.D., Hukin, A., Regan, N., Smith, J., 2011. The SuRFUK indicator set for sustainable remediation assessment. Contaminated Land Applications in Real Environments. CL: AIRE.

Bardos, R.P., Jones, S., Stephenson, I., Menger, P., Beumer, V., Neonato, F., Maring, L., Ferber, U., Track, T., Wendler, K., 2016. Optimising value from the soft re-use of brownfield sites. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2015.12.002.

Bardos, R.P., Thomas, H.F., Smith, J.W.N., Harries, N.D., Evans, F., Boyle, R., Howard, T., Lewis, R., Thomas, A.O., Haslam, A., 2018. The development and use of sustainability criteria in SuRF-UK's sustainable remediation framework. Sustain https://doi.org/ 10.3390/su10061781.

Bartke, S., Schwarze, R., 2015. No perfect tools: trade-offs of sustainability principles and user requirements in designing support tools for land-use decisions between greenfields and brownfields. J. Environ. Manag. 153, 11–24. https://doi.org/10.1016/j.jenvman.2015.01.040.

Bartke, S., Martinát, S., Klusáček, P., Pizzol, L., Alexandrescu, F., Frantál, B., Critto, A., Zabeo, A., 2016. Targeted selection of brownfields from portfolios for sustainable regeneration: user experiences from five cases testing the Timbre Brownfield Prioritization Tool. J. Environ. Manag. https://doi.org/10.1016/j.jenvman.2016.07.037.

Beames, A., Broekx, S., Schneidewind, U., Landuyt, D., van der Meulen, M., Heijungs, R., Seuntjens, P., 2018. Amenity proximity analysis for sustainable brownfield redevelopment planning. Landsc. Urban Plan. https://doi.org/10.1016/j.landurbplan.2017.12.003.

Bittens, M., Rein, A., Ruegner, H., Schwarze, R., Finkel, M., 2008. Cross Cutting Case Description Germany: Strategies for the Revitalization of Brownfield Areas in the Larger Potsdam Region (SINBRA) – Technology Demonstration Platform. Pp. 39–40.

Black, P., Stockton, T., 2009. Basic steps for the development of decision support systems. In: Marcomini, A., Suter II, G.W., Critto, A. (Eds.), Decision Support Systems for Riskbased Management of Contaminated Sites. Springer US, Boston, MA, pp. 1–27 https://doi.org/10.1007/978-0-387-09722-0_1.

British Geological Survey, 2019. Brownfield ground risk calculator. [WWW Document]. URL. https://www.bgs.ac.uk/research/engineeringGeology/urbanGeoscience/brownfield/home.html. (Accessed 25 February 2020).

British Geological Survey, 2020. Brownfield ground risk calculator. [WWW Document]. URL. https://www.bgs.ac.uk/geology-projects/brownfield-ground-risk-calculator/. (Accessed 2 December 2020).

Brombal, D., Wang, H., Pizzol, L., Critto, A., Giubilato, E., Guo, G., 2015. Soil environmental management systems for contaminated sites in China and the EU. Common challenges and perspectives for lesson drawing. Land Use Policy 48, 286–298. https:// doi.org/10.1016/J.LANDUSEPOL.2015.05.015.

Brundtland, G.H., Khalid, M., Agnelli, S., Al-Athel, S., Chidzero, B., 1987. Our Common Future New York 8.

Burinskiene, M., Bielinskas, V., Podviezko, A., Gurskiene, V., Maliene, V., 2017. Evaluating the significance of criteria contributing to decision making on brownfield land redevelopment strategies in urban areas. Sustain. 9, 759. https://doi.org/10.3390/su9050759.

CABERNET, 2006. Sustainable Brownfield Regeneration: CABERNET Network Report. University of Nottingham Land Quality Management Report.

Cannavó, F., 2012. Sensitivity analysis for volcanic source 57eotech5757 quality assessment and model selection. Comput. Geosci. 44, 52–59. https://doi.org/10.1016/j. cageo.2012.03.008.

Carlon, C., Pizzol, L., Critto, A., Marcomini, A., 2008. A spatial risk assessment methodology to support the remediation of contaminated land. Environ. Int. https://doi.org/ 10.1016/j.envint.2007.09.009.

Chen, J., Zhang, X., Zhu, Q., 2011. Multi-objective decision making for land use planning with ordered weighted averaging method. Syst. Eng. Procedia 2, 434–440. https:// doi.org/10.1016/j.sepro.2011.10.063.

Cipullo, S., Snapir, B., Prpich, G., Campo, P., Coulon, F., 2019. Prediction of bioavailability and toxicity of complex chemical mixtures through machine learning models. Chemosphere 215, 388–395. https://doi.org/10.1016/j.chemosphere.2018.10.056.

CL: AIRE, 2021. SuRF International. [WWW Document]. URL. https://www.claire.co.uk/ projects-and-initiatives/surf-international. (Accessed 6 April 2021).

Connaughton, J., Mbugua, L., 2008. Faster building for industry: NEDO (1983). Construction Reports 1944–98. John Wiley & Sons, Ltd, pp. 114–129 https://doi.org/10.1002/ 9780470758526.ch9.

Coulon, F., Jones, K., Li, H., Hu, Q., Gao, J., Li, F., Chen, M., Zhu, Y.-G., Liu, R., Liu, M., Canning, K., Harries, N., Bardos, P., Nathanail, P., Sweeney, R., Middleton, D., Charnley, M., Randall, J., Richell, M., Howard, T., Martin, I., Spooner, S., Weeks, J., Cave, M., Yu, F., Zhang, F., Jiang, Y., Longhurst, P., Prpich, G., Bewley, R., Abra, J., Pollard, S., 2016. China's soil and groundwater management challenges: lessons from the UK's experience and opportunities for China. Environ. Int. 91, 196–200. https://doi.org/10.1016/J. ENVINT.2016.02.023.

CPRE, 2020. Recycling Our Land: The State of Brownfield 2020 – An Updated Analysis of the Potential of Brownfield Land for New Homes.

Critto, A., Agostini, P., 2009. Using multiple indices to evaluate scenarios for the remediation of contaminated land: the Porto Marghera (Venice, Italy) contaminated site. Environ. Sci. Pollut. Res. 16, 649–662. https://doi.org/10.1007/s11356-009-0194-5.

Crook, A.D.H. (Tony), Whitehead, C., 2019. Capturing development value, principles and practice: why is it so difficult? Town Plan. Rev. 90, 359–381. https://doi.org/ 10.3828/tpr.2019.25.

Culshaw, M.G., Nathanail, C.P., Leeks, G.J.L., Alker, S., Bridge, D., Duffy, T., Fowler, D., Packman, J.C., Swetnam, R., Wadsworth, R., Wyatt, B., 2006. The role of web-based environmental information in urban planning-the environmental information system for planners. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2005.08.037.

Di Nardo, A., Bortone, I., Chianese, S., Di Natale, M., Erto, A., Francesco Santonastaso, G., Musmarra, D., 2019. Odorous emission reduction from a waste landfill with an optimal protection system based on fuzzy logic. Environ. Sci. Pollut. Res. 26, 14755–14765. https://doi.org/10.1007/s11356-018-2514-0.

Doetsch, P., Rüpke, A., Burmeier, H., 1998. Revitalisierung von Altstandorten versus Inanspruchnahme von Naturflächen. Gegenüberstellung der Flächenalternativen zur Gewerbl. Nutzung durch Qual. Quant. Und Monet. Bewertung der Ges. Potentiale und Eff. Texte. 15 p. 98.

El Bilali, A., Taleb, A., Brouziyne, Y., 2021. Groundwater quality forecasting using machine learning algorithms for irrigation purposes. Agric. Water Manag. 245, 106625. https:// doi.org/10.1016/j.agwat.2020.106625.

ESRI, 2020. ArcGIS StoryMaps. [WWW Document]. URL. https://storymaps.arcgis.com/. (Accessed 23 September 2020).

Fathizad, H., Ardakani, M.A.H., Heung, B., Sodaiezadeh, H., Rahmani, A., Fathabadi, A., Scholten, T., Taghizadeh-Mehrjardi, R., 2020. Spatio-temporal dynamic of soil quality in the central Iranian desert 58eotech58 with machine learning and digital soil

assessment techniques. Ecol. Indic. 118, 106736. https://doi.org/10.1016/j.ecolind.2020.106736.

Feo, G. De, De Gisi, S., 2014. Using MCDA and GIS for hazardous waste landfill siting considering land scarcity for waste disposal. Waste Manag. 34, 2225–2238. https://doi. Org/10.1016/j.wasman.2014.05.028.

Fraser, H., Smithson, J., Roe, N., Guppy, J., 2018. A Guide to Small Brownfield Sites and Land Contamination (C773). CIRIA, London.

Green, T.L., 2018. Evaluating predictors for brownfield redevelopment. Land Use Policy https://doi.org/10.1016/j.landusepol.2018.01.008.

Grubbs, F.E., 1969. Procedures for detecting outlying observations in samples. Technometrics 11, 1–21.

Herbst, H., Herbst, V., 2006. The development of an evaluation method using a geographic information system to determine the importance of wasteland sites as urban wildlife areas. Landsc. Urban Plan. https://doi.org/10.1016/j.landurbplan.2005.02.005.

Homes & Communities Agency, 2015. Guidance on dereliction, demolition and remediation costs. [WWW Document]. URL. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/414378/HCA_Remediation_ Cost_Guidance_2015.pdf. (Accessed 1 November 2019).

Horigan, V., De Nardi, M., Simons, R.R.L., Bertolini, S., Crescio, M.I., Estrada-Peña, A., Léger, A., Maurella, C., Ru, G., Schuppers, M., Stärk, K.D.C., Adkin, A., 2018. Using multicriteria risk ranking methodology to select case studies for a generic risk assessment framework for exotic disease incursion and spread through Europe. Prev. Vet. Med. 153, 47–55. https://doi.org/10.1016/j.prevetmed.2018.02.013.

Huang, I.B., Keisler, J., Linkov, I., 2011. Multi-criteria decision analysis in environmental sciences: ten years of applications and trends. Sci. Total Environ. https://doi.org/ 10.1016/j.scitotenv.2011.06.022.

Huysegoms, L., Cappuyns, V., 2017. Critical review of decision support tools for sustainability assessment of site remediation options. J. Environ. Manag. https://doi.org/ 10.1016/j.jenvman.2017.03.002.

Huysegoms, L., Rousseau, S., Cappuyns, V., 2019. Indicator use in soil remediation investments: views from policy, research and practice. Ecol. Indic. 103, 70–82. https://doi. Org/10.1016/j.ecolind.2019.03.048.

Jefferson, J.L., Gilbert, J.M., Constantine, P.G., Maxwell, R.M., 2015. Active subspaces for sensitivity analysis and dimension reduction of an integrated hydrologic model. Comput. Geosci. 83, 127–138. https://doi.org/10.1016/j.cageo.2015.07.001.

Kaufman, M.M., Rogers, D.T., Murray, K.S., 2005. An empirical model for estimating remediation costs at contaminated sites. Water Air Soil Pollut. https://doi.org/10.1007/ s11270-005-0214-0.

Kong, N., Zhang, T., Stonebraker, I., 2015. Evaluation of web GIS functionality in academic libraries. Appl. Geogr. https://doi.org/10.1016/j.apgeog.2014.11.017.

Kordi, M., Brandt, S.A., 2012. Effects of increasing fuzziness on analytic hierarchy process for spatial multicriteria decision analysis. Comput. Environ. Urban. Syst. 36, 43–53.

https://doi.org/10.1016/j.compenvurbsys.2011.07.004.

Kuhn, M., Johnson, K., 2013. Applied Predictive Modeling. Springer.

Kunapo, J., Dasari, G.R., Phoon, K.-K., Tan, T.-S., 2005. Development of a web-GIS based geotechnical information system. J. Comput. Civ. Eng. 19, 323–327. https://doi.org/ 10.1061/(ASCE)0887-3801(2005)19:3(323.

Kurina, F.G., Hang, S., Macchiavelli, R., Balzarini, M., 2019. Spatial predictive modelling essential to assess the environmental impacts of herbicides. Geoderma 354, 113874.

Li, X., Li, J., Sui, H., He, L., Cao, X., Li, Y., 2018. Evaluation and determination of soil remediation schemes using a modified AHP model and its application in a contaminated

coking plant. J. Hazard. Mater. 353, 300–311. https://doi.org/10.1016/j. jhazmat.2018.04.010.

Limasset, E., Bartke, S., Merly, C., Doisy, S., Dubromel, A., Pizzol, L., Martinát, S., Klusáček, P., Clozel, B., 2017. Prioritisation Strategies for Regional Brownfield Redevelopment: Perspectives & Feedback on Existing Tools and Approaches.

Liu, Y., van Oort, F., Geertman, S., Lin, Y., 2014. Institutional determinants of brownfield formation in Chinese cities and urban villages. Habitat Int. 44, 72–78. https://doi. Org/10.1016/J.HABITATINT.2014.05.005.

Liu, Y., Zhu, A.-X., Wang, J., Li, W., Hu, G., Hu, Y., 2019. Land-use decision support in brownfield redevelopment for urban renewal based on crowdsourced data and a presence-and-background learning (PBL) method. Land Use Policy 88, 104188. https://doi.org/10.1016/j.landusepol.2019.104188.

Madsen, D.Ø., 2016. SWOT analysis: a management fashion perspective. Int. J. Bus. Res. 16. https://doi.org/10.18374/IJBR-16-1.3.

Male, S., 2008. Faster building for commerce: NEDO (1988). Construction Reports 1944–98. John Wiley & Sons, Ltd, pp. 130–144 https://doi.org/10.1002/9780470758526.ch10.

Ministry of Housing Communities and Local Government, 2020. Local Digital Fund. [WWW Document]. URL. https://mhclgdigital.blog.gov.uk/category/local-digital/ local-digital-fund/. (Accessed 4 March 2020).

Mosadeghi, R., Warnken, J., Tomlinson, R., Mirfenderesk, H., 2015. Comparison of FuzzyAHP and AHP in a spatial multi-criteria decision making model for urban land-use planning. Comput. Environ. Urban. Syst. 49, 54–65. https://doi.org/10.1016/j. compenvurbsys.2014.10.001.

Odii, E.C., Ebido, C.C., Harder, M.K., 2019. A values-based approach for generating localized social indicators for use in sustainability assessment and decision making: test case of brownfield soft reuse in Nigeria. Sci. Total Environ. https://doi.org/10.1016/J. SCITOTENV.2019.135045.

Panagos, P., Liedekerke, M. Van, Yigini, Y., Montanarella, L., 2013. Contaminated sites in Europe: review of the current situation based on data collected through a European network. J. Environ. Public Health 2013. https://doi.org/10.1155/2013/158764.

Pérez, A.P., Peláez Sánchez, S., 2017. European Achievements in Soil Remediation and Brownfield Redevelopment. https://doi.org/10.2760/91268.

Peterle, G., 2018. New lines: critical GIS and the trouble of the map. Soc. Cult. Geogr. 19, 696–698. https://doi.org/10.1080/14649365.2018.1477178.

Pintér, L., Hardi, P., Martinuzzi, A., Hall, J., 2012. Bellagio STAMP: principles for sustainability assessment and measurement. Ecol. Indic. https://doi.org/10.1016/j.ecolind. 2011.07.001.

Pizzol, L., Critto, A., Marcomini, A., 2009. A spatial decision support system for the riskbased management of contaminated sites: the DESYRE DSS. Decision Support Systems for Risk-based Management of Contaminated Sites. Springer US, pp. 157–178 https://doi.org/10.1007/978-0-387-09722-0_8.

Pizzol, L., Critto, A., Agostini, P., Marcomini, A., 2011. Regional risk assessment for contaminated sites part 2: ranking of potentially contaminated sites. Environ. Int. 37, 1307–1320. https://doi.org/10.1016/j.envint.2011.05.010.

Pizzol, L., Zabeo, A., Klusáček, P., Giubilato, E., Critto, A., Frantál, B., Martinát, S., Kunc, J., Osman, R., Bartke, S., 2016. Timbre Brownfield Prioritization Tool to support effective brownfield regeneration. J. Environ. Manag. 166, 178–192. https://doi.org/10.1016/j. jenvman.2015.09.030.

Pollard, T.J., Chen, I., Wiens, J., Horng, S., Wong, D., Ghassemi, M., Mattie, H., Lindemer, E., Panch, T., 2019. Turning the crank for machine learning: ease, at what expense? Lancet Digit. Health 1, e198–e199. https://doi.org/10.1016/S2589-7500(19)30112-8.

Promentilla, M.A.B., Furuichi, T., Ishii, K., Tanikawa, N., 2008. A fuzzy analytic network process for multi-criteria evaluation of contaminated site remedial countermeasures. J. Environ. Manag. https://doi.org/10.1016/j.jenvman.2007.03.013.

Purucker, S.T., Stewart, R.N., Welsh, C.J.E., 2009. SADA: ecological risk based decision support system for selective remediation. In: Marcomini, A., Suter II, G.W., Critto, A. (Eds.), Decision Support Systems for Risk-based Management of Contaminated Sites. Springer US, Boston, MA, pp. 1–18 https://doi.org/10.1007/978-0-387-097220_11.

RESCUE, 2004. RESCUE regeneration of 63eotech63 sites in cities and urban environments. [WWW Document]. URL. http://www.eugris.info/displayproject.asp?Projectid= 4517. (Accessed 23 March 2020).

Rizzo, E., Pesce, M., Pizzol, L., Alexandrescu, F.M., Giubilato, E., Critto, A., Marcomini, A., Bartke, S., 2015. Brownfield regeneration in Europe: identifying stakeholder perceptions, concerns, attitudes and information needs. Land Use Policy 48, 437–453. https://doi.org/10.1016/j.landusepol.2015.06.012.

Rizzo, E., Pizzol, L., Zabeo, A., Giubilato, E., Critto, A., Cosmo, L., Marcomini, A., 2018. An information system for brownfield regeneration: providing customised information according to stakeholders' characteristics and needs. J. Environ. Manag. 217. https://doi. Org/10.1016/j.jenvman.2018.03.059.

Rodriguez-Galiano, V.F., Luque-Espinar, J.A., Chica-Olmo, M., Mendes, M.P., 2018. Feature selection approaches for predictive modelling of groundwater nitrate pollution: an evaluation of filters, embedded and wrapper methods. Sci. Total Environ. https:// doi.org/10.1016/j.scitotenv.2017.12.152.

Rosén, L., Norrman, J., Norberg, T., 2013. SCORE: Multi-Criteria Analysis (MCA) for sustainability appraisal of remedial alternatives 2013. SCORE: Multi-Criteria Analysis (MCA) for Susta, in: Second International Symposium on Bioremediation and Sustainable Environmental Technologies. Jack, Jacksonville, FL.

Rosén, L., Back, P.E., Söderqvist, T., Norrman, J., Brinkhoff, P., Norberg, T., Volchko, Y., Norin, M., Bergknut, M., Döberl, G., 2015. SCORE: a novel multi-criteria decision analysis approach to assessing the sustainability of contaminated land remediation. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2014.12.058.

Rothstein, H.R., Hopewell, S., 2009. Grey literature. The Handbook of Research Synthesis and Meta-analysis, 2nd ed. Russell Sage Foundation, New York, NY, US, pp. 103–125. Saaty, T.L., 1984. The analytic hierarchy process: decision making in complex

environments. In: Avenhaus, R., Huber, R.K. (Eds.), Quantitative Assessment in Arms Control: Mathematical Modeling and Simulation in the Analysis of Arms Control Problems. Springer US, Boston, MA, pp. 285–308 https://doi.org/10.1007/978-1-4613-2805-6_12.

Sajedi-Hosseini, F., Malekian, A., Choubin, B., Rahmati, O., Cipullo, S., Coulon, F., Pradhan, B., 2018. A novel machine learning-based approach for the risk assessment of nitrate groundwater contamination. Sci. Total Environ. https://doi.org/10.1016/j. scitotenv.2018.07.054.

Schädler, S., Finkel, M., Bleicher, A., Morio, M., Gross, M., 2013. Spatially explicit computation of sustainability indicator values for the automated assessment of land-use options. Landsc. Urban Plan. https://doi.org/10.1016/j.landurbplan.2012.12.002.

Schädler, S., Morio, M., Bartke, S., Finkel, M., 2012. Integrated planning and spatial evaluation of megasite remediation and reuse options. J. Contam. Hydrol. 127 (1–4), 88–100. https://doi.org/10.1016/j.jconhyd.2011.03.003.

Schädler, S., Morio, M., Bartke, S., Rohr-Zänker, R., Finkel, M., 2011. Designing sustainable and economically attractive brownfield revitalization options using an integrated assessment model. J. Environ. Manag. 92 (3), 827–837. https://doi.org/10.1016/j. jenvman.2010.10.026.

Smith, J.W.N., 2019. Debunking myths about sustainable remediation. Remediation 29, 7–15. https://doi.org/10.1002/rem.21587.

Söderqvist, T., Brinkhoff, P., Norberg, T., Rosén, L., Back, P.E., Norrman, J., 2015. Cost-benefit analysis as a part of sustainability assessment ofremediation alternatives for contaminated land. J. Environ. Manag. https://doi.org/10.1016/j.jenvman.2015.04.024.

Song, Y., Hou, D., Zhang, J., O'Connor, D., Li, G., Gu, Q., Li, S., Liu, P., 2018. Environmental and socio-economic sustainability appraisal of contaminated land remediation strategies: a case study at a mega-site in China. Sci. Total Environ. 610–611, 391–401. https://doi.org/10.1016/J.SCITOTENV.2017.08.016.

Sorvari, J., Seppälä, J., 2010. A decision support tool to prioritize risk management options for contaminated sites. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2009.12.026.

Stezar, I.C., Pizzol, L., Critto, A., Ozunu, A., Marcomini, A., 2013. Comparison of risk-based decision-support systems for brownfield site rehabilitation: DESYRE and SADA applied to a Romanian case study. J. Environ. Manag. https://doi.org/10.1016/j.

jenvman.2013.09.022.

Syms, P., 1999. Redeveloping brownfield land the decision making process. J. Prop. Invest. Financ. 17, 481–500. https://doi.org/10.1108/14635789910294903.

Tendero, M., Plottu, B., 2019. A participatory decision support system for contaminated brownfield redevelopment: a case study from France. J. Environ. Plan. Manag. 62, 1736–1760. https://doi.org/10.1080/09640568.2018.1512476.

Tucker, G.E., Whipple, K.X., 2002. Topographic outcomes predicted by stream erosion models: sensitivity analysis and 65eotech6565n comparison. J. Geophys. Res. Solid Earth 107, ETG 1-1-ETG, 1–16. https://doi.org/10.1029/2001JB000162.

UNEP, 2020. UNEP 65eotech6565ntal and Social Sustainability Framework (ESSF).

University of Brighton, 2016. WeValue: A Values-based Approach. [WWW Document]. URL. http://blogs.brighton.ac.uk/wevalue/?_ga=2.38694759.552889854.1584956524517564583.1582888175. (Accessed 23 March 2020).

Van Der Perk, M., Burema, J.R., Burrough, P.A., Gillett, A.G., Van Der Meer, M.B., Van Der Perk1, M., Burema1, J.R., Burrough1, P.A., Gillett2, A.G., Van Der Meer1, M.B., 2001. A GIS-based environmental decision support system to assess the transfer of longlived radiocaesium through food chains in areas contaminated by the Chernobyl accident. Int. J. Geogr. Inf. Sci. 15, 43–64. https://doi.org/10.1080/13658810010005552.

Van Liedekerke, M., Prokop, G., Rabl-Berger, S., Kibblewhite, M., Louwagie, G., 2014. Progress in the Management of Contaminated Sites in Europe. https://doi.org/10.2788/4658.

Vancauwenberghe, G., van Loenen, B., 2018. Exploring the emergence of open spatial data infrastructures: analysis of recent developments and trends in Europe. In: Saeed, S., Ramayah, T., Mahmood, Z. (Eds.), User Centric E-government: Challenges and Opportunities. Springer International Publishing, Cham, pp. 23–45 https://doi.org/10.1007/ 978-3-319-59442-2_2.

Velasquez, M., Hester, P., 2013. An analysis of multi-criteria decision making methods. Int. J. Oper. Res. 10 (2), 56–66.

Wu, G., Kechavarzi, C., Li, X., Wu, S., Pollard, S.J.T., Sui, H., Coulon, F., 2013. Machine learning models for predicting PAHs bioavailability in compost amended soils. Chem. Eng. J. 223, 747–754. https://doi.org/10.1016/J.CEJ.2013.02.122.

Yatsalo, B., Sullivan, T., Didenko, V., Gritsuk, S., Tkachuk, A., Mireabasov, O., Slipenkaya, V., Pichugina, I., Linkov, I., 2012. Environmental risk management with the use of multicriteria spatial decision support system DECERNS. Int. J. Risk Assess. Manag. 16, 175–198. https://doi.org/10.1504/IJRAM.2012.051254.

Zabeo, A., Pizzol, L., Agostini, P., Critto, A., 66eot, S., Marcomini, A., 2011. Regional risk assessment for contaminated site's part 1: vulnerability assessment by multicriteria decision analysis. Environ. Int. https://doi.org/10.1016/j.envint.2011.05.005.

Zadeh, L.A., 1965. Fuzzy sets. Inf. Control. 8, 338–353. https://doi.org/10.1016/S0019-9958 (65)90241-X.

Zhu, Y., Hipel, K.W., Ke, G.Y., Chen, Y., 2015. Establishment and optimization of an evaluation index system for brownfield redevelopment projects: an empirical study. Environ. Model. Softw. 74, 173–182. https://doi.org/10.1016/j.envsoft.2015.09.012.

2.7 Appendix

Table 2.4 Summary of research reviewed for this study.

APPLICATION	AUTHORS	TITLE	YEAR	Journal (if applicable)	Citations (December 2019)	Geographic location (continent)	Geographic location (country)
Ecological risk assessment	Critto, *et al*	Development of a site-specific ecological risk assessment for contaminated sites: Part I. A multi-criteria-based system for the selection of ecotoxicological tests and ecological observations	2007	Science of the Total Environment	45	Europe	Italy
	Semenzin *et al*.	Development of a site-specific Ecological Risk Assessment for contaminated sites: Part II. A multi-criteria-based system for the selection of bioavailability assessment tools	2007	Science of the Total Environment	29	Europe	Italy
Groundwater contamination assessment	Hepburn *et al*.	A framework and simple decision support tool for groundwater contamination assessment in an urban redevelopment precinct.	2019	Hydrogeology Journal	0	Oceania	Australia
Land use planning	Culshaw *et al*.	The role of web-based environmental information in urban planning-the environmental information system for planners	2006	Science of the Total Environment	38	Europe	UK
	Herbst and Herbst	The development of an evaluation method using a geographic information system to determine the importance of wasteland sites as urban wildlife areas	2006	Landscape and Urban Planning	27	Europe	Germany
	Chen *et al*.	A strategic classification support system for brownfield redevelopment	2009	Environmental Modelling and Software	69	Asia	China
	Chen *et al*.	Multi-Objective Decision Making for Land Use Planning with Ordered Weighted Averaging Method.	2011	Systems Engineering Procedia	13	Asia	China
	Schadler *et al*.	Designing sustainable and economically attractive brownfield revitalization options using an integrated assessment model	2011	Journal of Contaminant Hydrology	125	Europe	Germany

	Morio *et al*.	Applying a multi-criteria genetic algorithm framework for brownfield reuse optimization: Improving redevelopment options based on stakeholder preferences	2013	Journal of Environmental Management	56	Europe	Germany
	Schädler *et al*.	Spatially explicit computation of sustainability indicator values for the automated assessment of land-use options	2013	Landscape and Urban Planning	22	Europe	Germany
	Mosadeghi, R. *et al*.	Comparison of Fuzzy-AHP and AHP in a spatial multi-criteria decision making model for urban land-use planning	2015	Computers, Environment and Urban Systems	112	Oceania	Australia
	Bardos *et al*.	Optimising value from the soft re-use of brownfield sites	2016	Science of the Total Environment	28	Europe	UK
	Burinskienė *et al*.	Evaluating the Significance of Criteria Contributing to decision making on Brownfield Land Redevelopment Strategies in Urban Areas	2017	Sustainability	11	Europe	Lithuania
	Beames *et al*.	Amenity proximity analysis for sustainable brownfield redevelopment planning	2018	Landscape and Urban Planning	4	Europe	Belgium
	Liu *et al*.	Land-use decision support in brownfield redevelopment for urban renewal based on crowdsourced data and a presence-and-background learning (PBL) method	2019	Land Use Policy	1	Asia	China
	Bartke and Schwarze	No perfect tools: Trade-offs of sustainability principles and user requirements in designing support tools for land-use decisions between greenfields and brownfields.	2015	Journal of Environmental Management	50	Europe	Germany
	Abdullahi and Pradhan	Sustainable Brownfields Land Use Change Modeling Using GIS-based Weights-of-Evidence Approach.	2016	Applied Spatial Analysis and Policy	13	Asia	Malaysia
	Odii *et al*.	A values-based approach for generating localized social indicators for use in sustainability assessment and decision making: test case of brownfield soft reuse in Nigeria	2019	Science of The Total Environment	0	Asia	China

Remediation cost	Kaufman *et al*.	An empirical model for estimating remediation costs at contaminated sites	2005	Water, Air, and Soil Pollution	29	North America	USA
Remediation options/strategy	Hokkanen *et al*.	Multicriteria decision support in a technology competition for cleaning polluted soil in Helsinki	2000	Journal of Environmental Management	63	Europe	Finland
	Salt *et al*.	Development of a spatial decision support system for post-emergency management of radioactively contaminated land	2000	Journal of Environmental Management	14	Europe	UK
	Nasiri *et al*.	Prioritizing groundwater remediation policies: A fuzzy compatibility analysis decision aid	2007	Journal of Environmental Management	22	North America	Canada
	Promentilla *et al*.	A fuzzy analytic network process for multi-criteria evaluation of contaminated site remedial countermeasures	2008	Journal of Environmental Management	135	Asia	Japan
	Bello-Dambatta *et al*.	The Analytical Hierarchy Process for contaminated land management	2009	Advanced Engineering Informatics	53	Europe	UK
	Critto and Agostini	Using multiple indices to evaluate scenarios for the remediation of contaminated land: The Porto Marghera (Venice, Italy) contaminated site	2009	Environmental Science and Pollution Research	11	Europe	Italy
	Onwubuya *et al*.	Developing decision support tools for the selection of “gentle” remediation approaches	2009	Science of the Total Environment	52	Europe	UK
	Pizzol *et al*.	A spatial decision support system for the risk-based management of contaminated sites: The DESYRE DSS	2009	In: Decision Support Systems for Risk-Based Management of Contaminated Sites	12	Europe	Italy
	Sorvari and Seppälä	A decision support tool to prioritize risk management options for contaminated sites	2010	Science of the Total Environment	57	Europe	Finland

Remediation options/strategy	Yatsalo *et al*.	Environmental risk management with the use of multi-criteria spatial decision support system DECERNS	2012	International Journal of Risk Assessment and Management	12	Europe	Russia
	Bai, L. *et al*.	TOPSIS-Based Screening Method of Soil Remediation Technology for Contaminated Sites and its Application	2015	Soil and Sediment Contamination: An International Journal	7	Asia	China
	Rosen *et al*.	SCORE: A novel multi-criteria decision analysis approach to assessing the sustainability of contaminated land remediation	2015	Science of the Total Environment	75	Europe	Sweden
	Söderqvist *et al*.	Cost-benefit analysis as a part of sustainability assessment of remediation alternatives for contaminated land	2015	Journal of Environmental Management	62	Europe	Sweden
	Li *et al*.	Evaluation and determination of soil remediation schemes using a modified AHP model and its application in a contaminated coking plant	2018	Journal of Hazardous Materials	7	Asia	China
	Li *et al*.	Screening of groundwater remedial alternatives for brownfield sites: a comprehensive method integrated MCDA with numerical simulation	2018	Environmental Science and Pollution Research	2	Asia	China
Remediation options/strategy, land use planning	Schädler *et al*.	Integrated planning and spatial evaluation of megasite remediation and reuse options	2012	Journal of Contaminant Hydrology	66	Europe	Germany
Review	Agostini *et al*.	Decision support systems for contaminated land management: A review	2009	In: Decision Support Systems for Risk-Based Management of Contaminated Sites	11	Europe	Italy

	Agostini and Vega	Decision support systems (DSSs) for contaminated land management-Gaps and challenges	2009	In: Decision Support Systems for Risk-Based Management of Contaminated Sites	10	Europe	Italy
	Black and Stockton	Basic steps for the development of decision support systems	2009	In: Decision Support Systems for Risk-Based Management of Contaminated Sites	5	North America	USA
	Carlon *et al*.	Contaminated land: A multi-dimensional problem	2009	In: Decision Support Systems for Risk-Based Management of Contaminated Sites	5	Europe	Italy
	Marcomini *et al*.	Decision Support Systems for Risk-Based Management of Contaminated Site	2009	Book	40	Europe	Italy
	Stezar *et al*.	Comparison of risk-based decision-support systems for brownfield site rehabilitation: DESYRE and SADA applied to a Romanian case study	2013	Journal of Environmental Management	12	Europe	Romania
	Huysegoms and Cappuyns	Critical review of decision support tools for sustainability assessment of site remediation options	2017	Journal of Environmental Management	24	Europe	Belgium
Risk assessment	Carlon *et al*.	A spatial risk assessment methodology to support the remediation of contaminated land	2008	Environment International	55	Europe	Italy
Site ranking/indexing	Thomas	A GIS-based decision support system for brownfield redevelopment	2002	Landscape and Urban Planning	78	North America	USA

	Pizzol, L. *et al*	Regional risk assessment for contaminated sites Part 2: Ranking of potentially contaminated sites	2011	Environment International	40	Europe	Italy
	Agostini *et al*.	Regional risk assessment for contaminated sites Part 3: Spatial decision support system	2012	Environment International	33	Europe	Italy
	Chrysochoou *et al*.	A GIS and indexing scheme to screen brownfields for area-wide redevelopment planning	2012	Landscape and Urban Planning	71	North America	USA
	Zhu *et al*.	Establishment and optimization of an evaluation index system for brownfield redevelopment projects: An empirical study.	2015	Environmental Modelling and Software	26	Asia	China
	Bartke *et al*.	Targeted selection of brownfields from portfolios for sustainable regeneration: User experiences from five cases testing the Timbre Brownfield Prioritization Tool	2016	Journal of Environmental Management	45	Europe	Germany
	Pizzol *et al*.	Timbre Brownfield Prioritization Tool to support effective brownfield regeneration	2016	Journal of Environmental Management	48	Europe	Italy
	Sam *et al*.	'A multi-attribute methodology for the prioritisation of oil contaminated sites in the Niger Delta'	2017	Science of the Total Environment	9	Europe	UK
Stakeholder engagement	Rizzo *et al*.	Brownfield regeneration in Europe: Identifying stakeholder perceptions, concerns, attitudes, and information needs.	2015	Land Use Policy	58	Europe	Italy
	Tendero and Plottu	A participatory decision support system for contaminated brownfield redevelopment: a case study from France	2019	Journal of Environmental Planning and Management	0	Europe	France
Vulnerability assessment	Zabeo *et al*.	Regional risk assessment for contaminated sites Part 1: vulnerability assessment by multicriteria decision analysis.	2011	Environment International	56	Europe	Italy

3 DIGITAL TOOLS FOR BROWNFIELD REDEVELOPMENT: STAKEHOLDER PERSPECTIVES AND OPPORTUNITIES

Ellis B. Hammond[1, 2], Frederic Coulon[2], Stephen H. Hallett[2], Russell Thomas[3], Drew Hardy[4], Darren J. Beriro[1*].

[1]British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK.

[2]School of Water, Energy and Environment, Cranfield University, Cranfield, MK43 0AL, UK.

[3]WSP, Kings Orchard, 1 Queen St, Bristol, BS2 0HQ, UK

[4]Groundsure, Sovereign House, Church Street, Brighton BN1 1UJ, UK

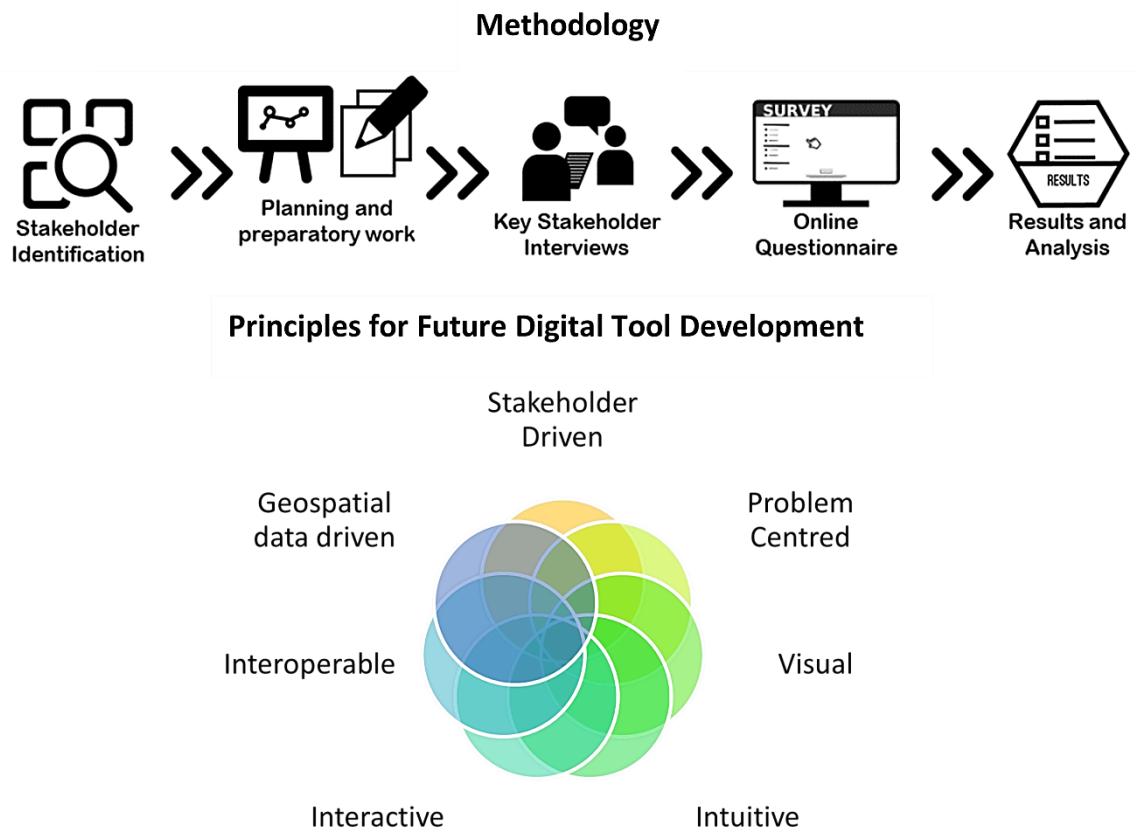
Abstract:

Brownfield redevelopment is a complex process often involving a wide range of stakeholders holding differing priorities and opinions. The use of digital systems and products for decision making, modelling, and supporting discussion has been recognised throughout literature and industry. The inclusion of stakeholder preferences is an important consideration in the design and development of impactful digital tools and decision support systems. In this study, we present findings from stakeholder consultation with professionals from the UK brownfield sector to inform the design of future digital tools and systems. Our research investigates two broad themes; digitalisation and the use of digital tools across the sector; and perceptions of key brownfield challenge areas where digital tools could help better inform decision-makers. The methodology employed for this study comprises the collection of data and information using a combination of interviews and an online questionnaire. The results from these methods were evaluated both qualitatively and quantitatively. Findings reveal a disparity in levels of digital capability between stakeholder groups including between technical stakeholder types, and that cross-discipline communication of important issues may be aided by the development

of carefully designed digital tools. To this end, we present seven core principles to guide the design and implementation of future digital tools for the brownfield sector. These principles are that future digital tools should be: (1) Stakeholder driven, (2) Problem centred, (3) Visual, (4) Intuitive, (5) Interactive, (6) Interoperable, and (7) Geospatial data-driven.

Keywords: Brownfield Redevelopment, Stakeholder Engagement, Online Questionnaire, Digital Tools, Decision Support Systems.

Graphical Abstract:



3.1 Introduction

Deindustrialisation across the UK, Europe and other parts of the world has led to the abandonment of former industrial sites, or brownfields, which pose environmental, social, and economic redevelopment challenges for countries and communities (Naidu et al., 2021). Brownfields can be usefully described as: "sites that have either been affected by the former uses of the site and the surrounding land, are derelict or underused; or have real or perceived contamination problems; and are mainly in developed urban areas and require intervention to bring them back to beneficial use" (CABERNET, 2006).

In the UK, it is recognised that brownfield sites represent a significant underutilised housing resource (MHCLG, 2020). Under the Town and Country Planning (Brownfield Land Register) Regulations 2017, local authorities are required to create and maintain a Brownfield Register for all brownfield sites that are available for housing development, irrespective of their planning status (MHCLG, 2017), meaning that the Brownfield Register sites are only a subset of all brownfield land in the UK. The Campaign to Protect Rural England (CPRE) (a charity lobbying to prevent unnecessary development on greenfield sites) estimates that current sites on Brownfield Registers across England can provide space for a minimum of 1,077,292 dwellings (CPRE, 2020). In the 2020 spending review, the UK government released four hundred million pounds (£400 m) as part of the Brownfield Land Release Fund (BLRF) under the National Home Building Fund (OGP, LGA & MHCLG, 2021). This release of funds demonstrates the UK government's commitment to developing brownfield sites as a priority to meet house building targets.

The specific planning and development process for brownfield sites can depend on project or site-specific requirements as well as local or national regulations. Figure 3.1 (from (Hammond et al., 2021)) shows the typical process for redeveloping brownfield sites and managing the potential risk posed by contaminated land, highlighting the relationships between land use planning scale, development stage, uncertainty in decision making, and data needs.

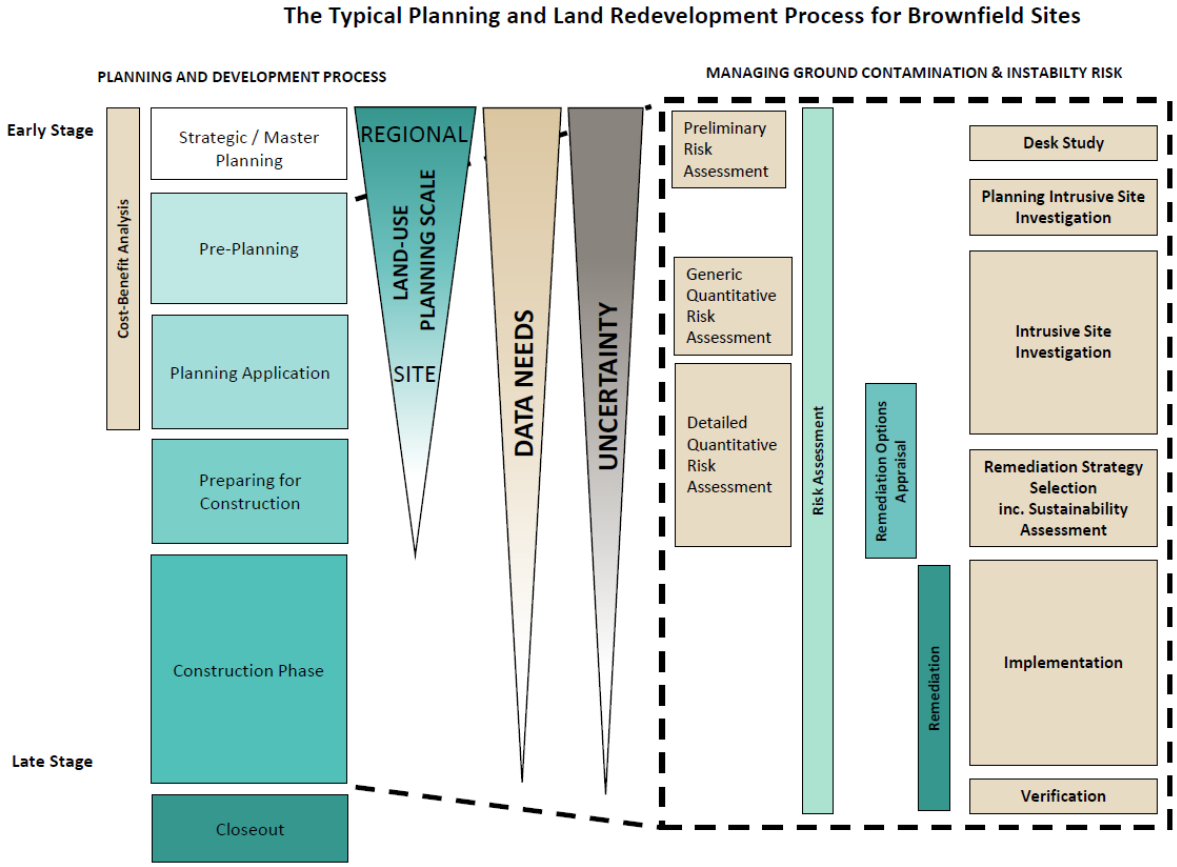


Figure 3.1 The typical planning and land development process for brownfield sites indicating the relationship between steps within each domain showing how scale, data and uncertainty reduce over time (Hammond et al., 2021).

Making decisions around land use requires consideration of many different factors in a structured manner to allow the best possible decision to be undertaken (Guarini et al., 2018). Deciding whether brownfield land is safe and suitable for its intended use requires consideration of environmental (e.g., pollution) social (e.g., proximity to infrastructure) and economic (e.g., house prices) factors as well as attitudes of stakeholders including

the public toward the redevelopment project (Loures and Vaz, 2018). The complex interactions between ground issues caused by post-industrial legacy and stakeholder preferences result in the need for a considered strategy when dealing with brownfield redevelopment (CABERNET, 2006; Hammond et al., 2021; Rizzo et al., 2015). Compromise can be difficult to achieve because of a lack of information acquisition and exchange (Alexandrescu et al., 2017; Cappai et al., 2019). The US Environmental Protection Agency (US EPA) defined 5 steps for 'Successful Brownfield Redevelopment', focusing on community and stakeholder interaction (US EPA, 2019). Research in both academic literature and industrial guidance has shown that brownfield decision-makers must involve all stakeholders (i.e., local communities) within the redevelopment process to ensure a successful and mutually beneficial project (Bartke et al., 2016; Billger et al., 2017; Washbourne et al., 2020).

There are many mechanisms for decision-makers and other brownfield professionals to engage with stakeholders (i.e., developers, consultants, and land-use planners) (Rizzo et al., 2015). Firstly, stakeholder engagement led by the planning system, where stakeholder consultation is required by the national, regional, or local planning policy (MHCLG, 2019). Secondly, project-specific campaigns led by developers and development schemes, where a small circle of stakeholders unique to a certain redevelopment scheme are consulted about their preferences and desires for a project. This is generally achieved through focus groups, workshops, polling, and interview-like discussion. Third, large-scale stakeholder engagement, where consultation is carried out by public interest groups, national government, or academics. This usually also includes the involvement of focus groups, workshops, and interviews, but also the use of methods designed to survey a larger number of stakeholders, such as online questionnaires. Stakeholder engagement of

this type typically proceeds an investigative project, such as research or the development of a new product (Morgan, 1996), for example, new digital solutions to solve problems identified from stakeholder research. Recent work by Wilson and Tewdwr-Jones (2021) explores stakeholder engagement for planning through digital methods. To encourage engagement and elicit information from a wide group of stakeholders, a multi-level strategy for stakeholder participation could be implemented. This could involve the use of digital and non-digital methods alongside each other, a combination of face-to-face discussion, workshops, and interviews, combined with digital surveys, public polls, and social media engagement campaigns (Wilson and Tewdwr-Jones, 2021).

For this research, we have defined digitisation as: 'the conversion of paper-based or analogue information into digital format' whereas we define digitalisation as: 'the use of digital technologies to change and/or improve the way an organisation carries out their operations'.

Digital tools and technology have long been used by decision makers around the world who are involved with urban planning and development. GIS and mapping tools are often used to inform land-use planning in urban areas (Wang et al., 2015). Many tools have been developed to assist in the allocation of precious urban land for a variety of uses, from industrial land (Ruiz et al., 2012) to land for the generation of renewable energies (Beriro et al., 2022; Ferrari et al., 2022; Rylatt et al., 2001). Digital tools are often used to facilitate discussion with stakeholders and visualise challenges for urban regeneration (Billger et al., 2017) allowing better informed decisions to be made. More recently in the urban development sector technologies have been developed to support the creation of so-called *Smart Cities* (Stratigea et al., 2015) where the infrastructure of cities actively collects data to manage services and resources and support city planning (European

Commission, 2022). These digital tools support smart city development by mapping existing land use and assets, real-time data collection, modelling the urban environment, improving communicating between stakeholders, and identifying public priorities for smart city development policies (Simonofski et al., 2021). Similarly, digital technologies have been developed to assess sustainable development options to improve climate change resilience in urban areas (Balogun et al., 2020). Within the UK brownfield sector, digital tools are often used to support decision makers throughout the brownfield redevelopment process, this includes site selection and planning as well as site development activities (Figure 3.1). These digital tools vary in complexity and application, for example, spreadsheets containing statistical models to assess contamination (CL: AIRE, 2020) and proprietary post-site investigation soil logging software, HoleBASE™ (Bentley Systems, 2021a), or continuous monitoring ground gas monitoring systems (Schloemer et al., 2013). The use of AutoCAD software (or similar) for technical drawings or site plans is also commonplace across the brownfield redevelopment sector. Additionally, Geographical Information Systems (GIS) are utilised during several tasks that rely on geospatial data throughout the redevelopment process (Figure 3.1), from early-stage decisions like site selection and appraisal (Nogués and Arroyo, 2016), to late-stage tasks such as site investigation design, and 3D modelling of contamination (Velimirovic et al., 2020). The use of digital tools has become so important that innovation and advances in digital technologies are often recognised by industry awards (Environment Analyst, 2021).

In the academic literature, over the past two decades, digital tools and decision support systems (DSSs) have been used and developed to support brownfield decision-makers across the world (Hammond et al., 2021). Existing DSSs have been applied to many

different brownfield applications throughout the development process, including, remediation technology selection, land-use planning and site-selection, contamination modelling, as well as numerous other specialist applications.

The incorporation of stakeholder preference, through well-designed stakeholder analysis and engagement, is crucial in digital tool development (Leonidou et al., 2020) particularly; requirements gathering, ideation, and development. Existing stakeholder engagement for brownfield digital tool development has typically consisted of consulting a small number of experts focussing on one aspect such as remediation technology selection or modelling groundwater contamination plumes (Hammond et al., 2021).

Recent review work in the academic literature has discussed the need for brownfield digital tools and DSSs should seek to become more holistic in their scope, conducting wide-ranging stakeholder research (Drenning et al., 2022; Hammond et al., 2021). Findings from existing research show that the scope of stakeholder engagement for digital tool development should also be widened to assess a greater variety of issues and include input from a wider variety of stakeholders. Doing this would offer greater inclusivity of all views and the introduction of different perspectives for redevelopment options by highlighting the benefits and drawbacks, leading to improved decision making (Drenning et al., 2022; Hammond et al., 2021). Digital tool development projects that implement this stakeholder engagement approach have the potential to not only solve their specific problems but also to support communication across stakeholder groups and disciplines. By surveying stakeholders from outside of the project (i.e., large-scale stakeholder consultation), novel intelligence and unanticipated findings could be elucidated, benefiting both the individual project, but also more general brownfield applications.

This paper presents findings from a stakeholder consultation campaign involving UK brownfield and contaminated land professionals conducted in 2020 and 2021. The research was designed to ascertain the level of digitalisation within the UK brownfield sector, to highlight key brownfield redevelopment issues. And to identify opportunities for digital tool development to enhance brownfield decision making throughout the planning and redevelopment process.

3.2 Methodology

The method chosen to elicit the views of stakeholders in the brownfield development sector comprises five steps and aligns with the Interaction Design Foundation's 'Design Thinking' methodology (Interaction Design Foundation, 2022) to focus the research on specific end users and problem areas. The five steps for stakeholder consultation are (1) stakeholder identification and mapping; (2) planning and preparation of information elicitation activities; (3) key stakeholder semi-structured interviews; (4) large-scale online questionnaire; and (5) analysis and interpretation of results.

3.2.1 Stakeholder Identification

Stakeholder identification and mapping was undertaken through preliminary expert discussion in the research team and reading of literature concerning stakeholder engagement in the brownfield sector (Bartke et al., 2016; Bartke and Schwarze, 2015; Huysegoms et al., 2019; Rizzo et al., 2015; Song et al., 2018). These stakeholder categories were then grouped using a stakeholder map with regard to their involvement in the redevelopment of brownfield sites. (Figure 3.2). Three stakeholder categories were established as follows: (1) Core stakeholders, roles directly involved with the day-to-day planning, redevelopment, and management of brownfield sites, (2) Involved stakeholders, organisations that support and influence the brownfield redevelopment process by

supporting core stakeholders through research, financial and legal advice, regulatory support, or developing new methods and technologies, and (3) Informed stakeholders, parties not directly involved in the day-to-day redevelopment of brownfield sites. This information then allowed us to identify which stakeholders to interview and survey, and which stakeholders are less involved with the brownfield redevelopment process.

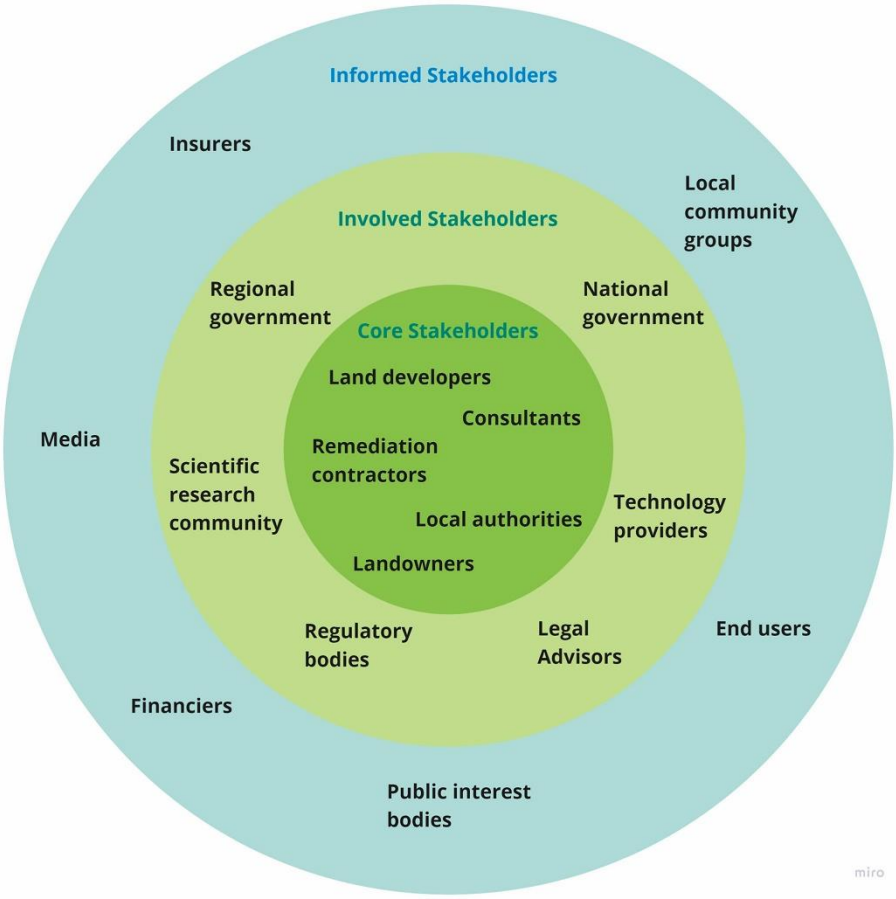


Figure 3.2 Stakeholder groups identified and mapped based on their involvement in the brownfield redevelopment process.

3.2.2 Planning and preparation

Prior to contacting the stakeholders identified in Step 1, scoping and design of an online questionnaire was conducted to review and identify common brownfield and data issues. This involved researching existing and emerging issues for brownfield redevelopment, as well as the adoption and application of digital tools within the sector. Consultation of the

academic literature and other publications, trade magazines, government, and public sector guidance was undertaken, including the publication of a critical review of academic literature (Hammond et al., 2021). These findings were then discussed with the research team to ensure the survey was technically sound and relevant. Following this scoping exercise, commonly used methods (Morgan, 1996; Rizzo et al., 2015) were selected to elicit information including semi-structured informal interviews (face-to-face, virtual, and group sessions) and the use of online questionnaires. At this stage, the online questionnaire structure and questions were drafted and finalised following an analysis of insights from key stakeholder interviews.

3.2.3 Key stakeholder interviews

Interviews with experts from the key technical stakeholder categories were conducted to validate understanding and assumptions from step two (planning and preparation) and to aid in the design of the large-scale online stakeholder questionnaire. A semi-structured interview method was used (Longhurst, 2016). Interviews were conducted, initially in-person, and then virtually after COVID-19 restrictions were imposed in the UK. Five experts from the areas of consultancy, remediation, scientific research, and data services were contacted. These stakeholder types were selected as they are exposed to a diversity of problems and roles across the sector and therefore, they are knowledgeable about a range of issues. The semi-structured interviews implemented a standardised set of questions to act as a guide for discussion with stakeholders and experts. These questions (Appendix 3.7.1) consisted of two profiling questions, four questions assessing their current levels of digitalisation, and three questions seeking to identify key brownfield issues from their perspective. They were used to ensure replicability between the individual interviews and to allow for direct comparison between stakeholder groups.

This approach allowed for a better understanding of the key issues and the creation of stakeholder personas (Appendix 3.7, Table 3.4), in turn allowing the questionnaire to be designed in the best possible way.

3.2.4 Online questionnaire

The online questionnaire was designed to investigate issues identified during key stakeholder interviews and also to be aimed at typical brownfield stakeholders (Table 3.1). The questions were based on five types including: (1) open, (2) closed, and (3) ranking questions, along with (4) Likert scale questions and (5) free text boxes. Open question styles were used to allow respondents to give unrestrained free responses. By contrast, on certain specific issues (such as common digital tools used for decision making) closed questions and ranking questions were used to ensure consistent answering styles, to allow direct and easy quantification and analysis of results with a comparison between stakeholder groups. Similarly, a Likert scale approach was used to record stakeholder attitudes and to directly compare against other stakeholders.

The questionnaire contained 29 questions, partitioned into three main sections (Appendix 3.7.2). The first section contained six questions about the respondent, including contact details, type of stakeholder, typical projects, seniority, and experience. The second section contained ten questions about digitalisation and digital tools the stakeholders and their organisation typically use to make decisions. The final section included six questions concerning key brownfield redevelopment issues.

The questionnaire was developed and hosted using the Qualtrics™ Online Survey Software (Qualtrics, 2021). The questionnaire was distributed through a variety of channels, including targeted distribution to fifty experts (Consultants = 19, Regulators = 3, Remediation Contractors = 10, National Government = 5, Local Authority Planning =

10, Scientific research community = 3) in the UK brownfield sector, industry mailing list, Contaminated Land Management Discussion list (~1400 members) (JISCMail, 2022), contaminated land/brownfield professional bodies, including CL: AIRE, 2022 and SoBRA (Society of Brownfield Risk Assessment) (SoBRA, 2022) (~>3000 members), and distribution through social media channels including LinkedIn® and Twitter. The questionnaire was run over nine weeks from 20th July 2020, until 21st September 2020.

3.2.5 Analysis and interpretation

Key stakeholder interviews: Qualitative data resulting from interviews were transcribed and analysed manually to identify the key themes and intelligence. This approach was used both to create stakeholder personas (Appendix 3.7, Table 3.4) and to support the design of the online questionnaire.

Questionnaires: Quantitative and qualitative data resulting from the online questionnaire were collected automatically using the Qualtrics ™ software. The Qualtrics ™ software platform was used to generate automatic graphical, tabulated, and statistical summaries of the quantitative response, and to group responses based on other question responses (i.e., stakeholder type). Prior to analysis, data cleaning of the textual responses was carried out. This involved correcting spelling and grammatical errors in responses to aid the automatic analysis of responses. Qualitative responses from the questionnaire were analysed with a combination of manual textual analysis and automatic qualitative analysis using the Nvivo ™ software (QSR, 2021). Keywords and themes were identified coded and quantified using a combination of automatic and manual coding. The automatic coding is built into Nvivo ™ and operates by analysing the uploaded text and identifying and quantifying common keywords, sentiments, and themes. By contrast, manual coding achieves the same, but the user identifies the instances. Word-cloud graphics were also

generated in Nvivo ™ and Qualtrics ™ software for use in this study. These are natively within the software with the only intervention being to remove irrelevant common English words (e.g., the, and & etc.) Insights generated from the quantitative and qualitative analyses were then used to map and correlate responses among the key stakeholders to elicit their views on the opportunities that digitalisation offers to the brownfield redevelopment sector.

3.3 Results and discussion

3.3.1 Stakeholder identification

The generation of stakeholder types was achieved through means of literature review and discussion within the research team. This resulted in the identification of 17 different stakeholder categories (Table 3.1). As outlined in section 3.2.1, the stakeholder types were grouped into three categories: Core Stakeholders, Involved Stakeholders and, Informed Stakeholders (Figure 3.2).

Table 3.1 Stakeholder Categories.

	Stakeholder Category	Profile
1	**National government**	Ministerial and non-ministerial departments responsible for land redevelopment.
2	**Regional government**	Regional and local authorities concerned with planning, spatial planning, and management of land resources.
3	**Local government**	
4	**Regulatory bodies**	Protection agencies concerned with the environment, soil, water, waste, Health & Safety.
5	**Public interest bodies**	Non-Governmental Organisations (NGOs), campaign groups, Chartered Institutions.
6	**Landowners**	Land/Site owners, or persons responsible for contaminated sites, liable parties.
7	**Local community groups**	Residents and/or local businesses organised into groups on local social issues.
8	**Developers**	Agents purchasing sites/land to improve and develop it for re-sale to the public or other organisations, including housebuilders, commercial and industrial developers.
9	**Consultants**	Environmental engineers, ecologists, planners, designers, civil engineers, geotechnical engineers etc.
10	**Technology providers**	Organisations seeking to develop and sell environmental remediation technology and solutions.

11	**Contractors**	Organisations specialising in conducting works such as remediation, construction, groundworks, utilities.
12	**Financiers**	Private or public organisations, investing or lending money for the development of sites/projects. Such organisations may also advise other organisations on financial matters.
13	**Insurers**	Organisations that support risk transfer, evaluating ongoing risk or carrying residual risk for developments.
14	**Scientific research community**	Researchers, academics, and students conducting research and development advancing the understanding of brownfield issues.
15	**Media**	Media reporting on developments and issues of public interest. Media organisations may be used to promote the success of a redevelopment project.
16	**End users**	The final end-users of a development – seen as a receptor in the SPR linkage model.
17	**Others**	Any other stakeholder relevant to brownfield redevelopment.

3.3.2 Initial stakeholder interviews

The following subsections detail findings from interviews with the five key stakeholders (Section 3.2.3), separated into the two themes of our investigation.

Digital Tools: The five interviews conducted provided valuable insights into current stakeholder digitalisation across the brownfield sector. Results indicate that many businesses and organisations across the sector are currently undergoing a 'digital transformation' (a transition from paper-based or disparate digital methods to integrative digital ways of working). Consultants state that this is especially true for how they carry out fieldwork with the increased use of GIS and Bluetooth systems for recording field observations and sampling locations. These systems are allowing them to send and share data more efficiently across systems and software platforms, in the field and when they are processing data from fieldwork. These include AutoCAD™ software to produce technical drawings and models and the increased use of post-site investigation software (such as HoleBASE ™ and GINT ™ (Bentley Systems, 2021a, Bentley Systems, 2021b).

Despite this growing trend for the implementation of new digital workflows, all interviewees identified several challenges such as different individuals' project

management styles (i.e., attitudes to risk and time allowances for key processes) often resulting in inconsistencies in the quality and completeness of the data. For example, less risk-averse clients may choose a cheaper and quicker site investigation meaning that the resolution of data around ground conditions may be poor. Similarly, data from previous site investigations are often disparate, being held in a non-structured manner within individual company databases & networks. This means that data and information are often either not used or overlooked entirely.

The interviewees all confirmed that their organisations were receptive to new developments and digital techniques and would be keen to adopt new digital tools where this would benefit their operations. Similarly, interviewees, particularly consultants, noted the sector should be able to evolve and embrace new technologies to "future-proof" the sector, allowing for "stakeholders within the sector to provide innovative solutions and services to their clients and the public".

Key Brownfield Issues: Generally, interviewees shared the same foremost issue, the cost of redeveloping brownfield sites. Their experiences highlighted the biggest cause of the failure of brownfield projects as the failure of developers and supporting organisations (e.g., contractors, consultants, local government) to estimate costs accurately throughout site redevelopment programmes. A shared concern was that "abnormal and unexpected ground conditions can often lead to cost increases and delayed completion dates" – Remediation Contractor, something also reported in the literature (Ameller et al., 2020; Connaughton and Mbugua, 2008; Male, 2008). However, the consultants and remediation contractor pointed out that sometimes, ground conditions are better than initially thought, and projects can finish earlier than planned, resulting in lowered costs.

Another aspect of importance noted was that the lack of understanding of the redevelopment process can lead to problems, highlighting that having a large group of project stakeholders can lead to a conflict of preferences and attitudes to risk and development opportunities. One of the consultants noted that “some developers don’t place enough importance on transport planning and as a result, a development has poor links and access to sites, and this can often make the development unviable”.

A commonly expressed view by consultants was that brownfield sites are typically developed for housing or strategic logistical developments. With logistic/commercial developments there is often a short planning program with a quick turnaround on high-value purchases. As a result, there is a “need to be able to have accurate and early estimates of expected risk and associated costs” – Consultant, for redeveloping such brownfield sites.

3.3.3 Online Questionnaire

The online questionnaire was distributed to an estimated 4000 potential participants and recorded 150 responses. However, if partial responses are removed the total number of full responses dropped to 98. The analysis did not segregate partial completion responses as they provide useful information.

All responses to the questionnaire can be found in the appendix (Table 3.5). Questionnaire respondents originated from a wide range of stakeholder groups (Figure 3.3) and represent a range of seniorities and experience levels (Appendix 3.7,Table 3.6). As shown by Figure 3.3, the majority of questionnaire respondents were consultants, when asked to specify, all of them stated that they are a geoenvironmental or geotechnical consultant. Local Authorities planning and development roles make up the second-largest respondent type, followed by similar numbers of regulators, national government, developers and landowners. The majority of stakeholders who responded to the questionnaire were at a senior level or above (62%) with more than 15 years' experience (48%) and the majority were qualified to a master's degree or doctorate level (71%).

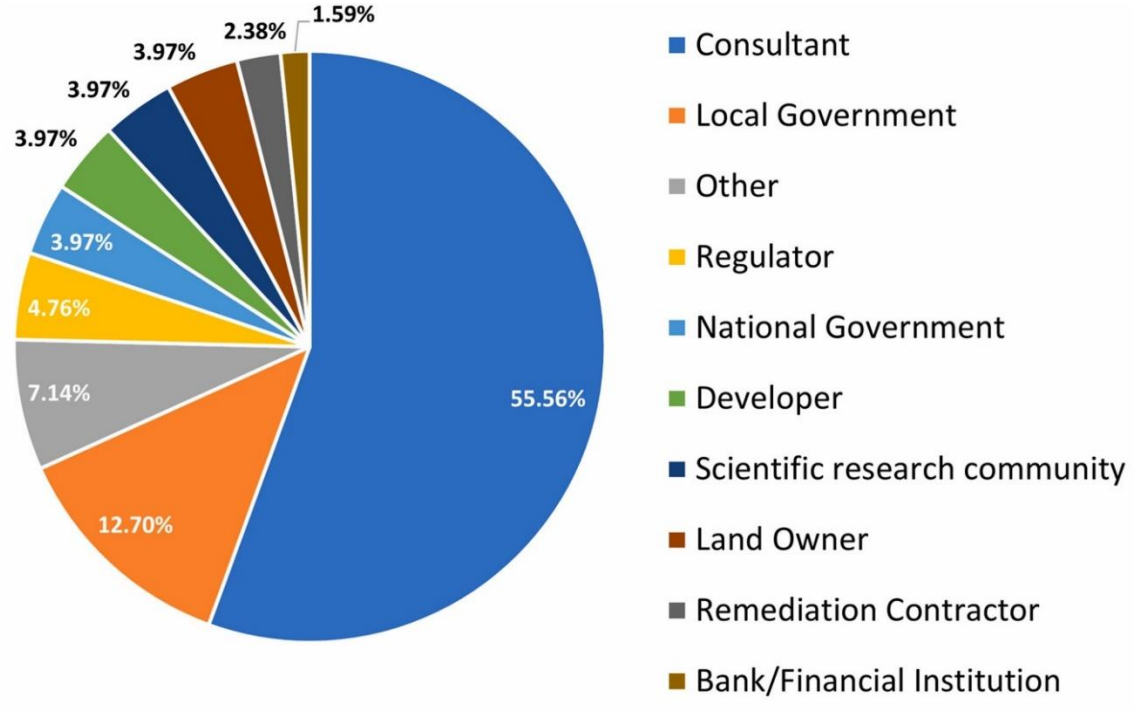


Figure 3.3 Questionnaire response by stakeholder type.

3.3.3.1 Digitalisation

The majority of the respondents (81%) self-assessed as having a 'moderately' or 'very digitally enabled' workflow (where they use a variety of digital tools as part of their daily tasks), with a smaller number (8%) self-assessing as extremely digital. The following

subsections present digitalisation question responses grouped into key stakeholder types allowing us to evaluate stakeholder attitudes across the sector.

Figure 3.4 is a plot of the digital capabilities of the stakeholder who responded to the questionnaire. Observations from data produced by the questionnaire suggest stakeholders fall into one of four types; (1) Highly Digital – The use of multiple digital tools frequently throughout their decision making process, (2) Moderately Digital – The use of multiple digital tools less frequently throughout their decision making process, (3) Somewhat Digital – the use of a smaller range of digital tools, but a high reliance on these tools in their decision making process, (4) Less digital – The use of a small range of digital, infrequently through their decision making process.

From data gathered in the online questionnaire, we observed that there is a trend for stakeholders that use lots of tools to have a greater dependency on them for decision making when compared to those that use fewer digital tools (Figure 3.4).

Insights from this plot of digital capabilities (Figure 3.4) show a few potential ways in which new digital tool development may help different stakeholders. For example, for stakeholders such as developers and remediation contractors, digital needs may be in upskilling in digital workflows and adoption of already present digital tools. More digitally capable stakeholders such as consultants may be better aided with digital tools

that fit into their already established digital workflow, or by novel digital tools that do something different than existing tools and systems.

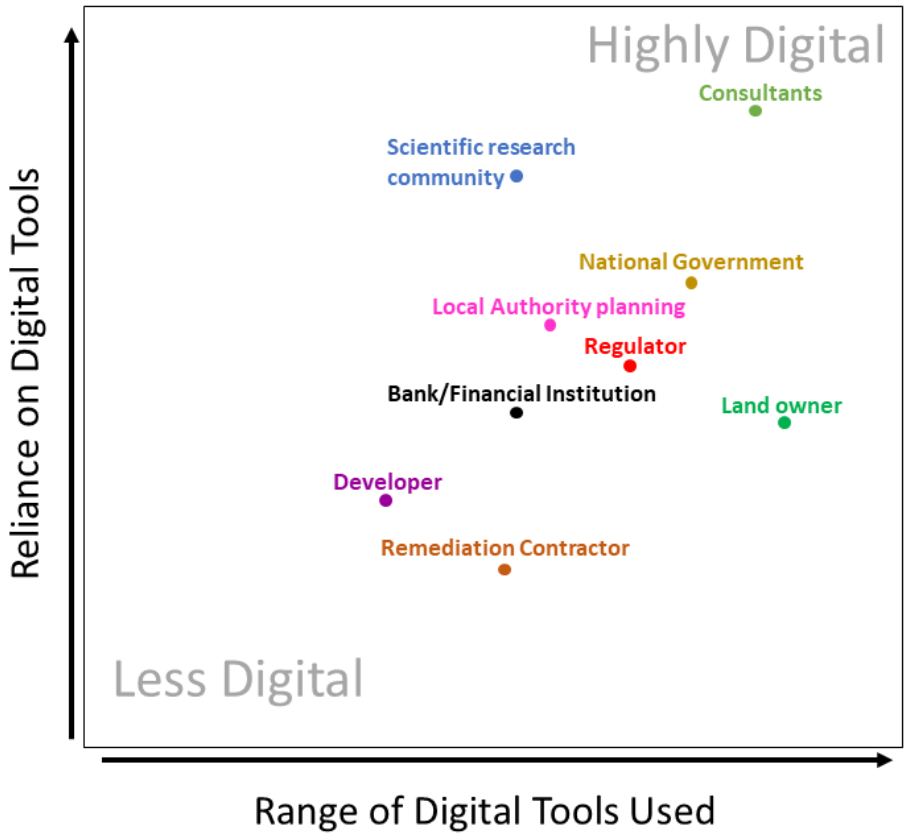


Figure 3.4 Use and reliance on digital tools across stakeholder types.

3.3.3.1.1 Remediation contractors

Two of the three remediation contractors reported that their organisations were 'moderately digital', with one reporting 'not at all digital', basing their decisions on the results of digital tools used only infrequently. This may indicate that remediation contractors are not as digitally enabled as other stakeholders. However, remediation contractors often work for larger civil engineering contractors that frequently utilise digital systems, such as Building Information Modelling (BIM) systems. This perhaps indicates that the wider project team associated with remediation may be more digitally enabled. Remediation contractors mostly use Excel and AutoCAD ™ software mainly to produce drawings and models to support remediation design, execution, and validation.

A wide variety of data is used by remediation contractors but mostly comprises site investigation data, including soil and rock logs, chemical test results and geotechnical test results. Environmental spatial data and non-spatial data are often used by remediation contractors, and environmental data reports are often purchased or inherited from previous Site Investigation (SI)/Ground Investigation (GI). Most remediation contractors agree that their current systems are of high enough quality to carry out their tasks. This may indicate that future digital tools may be of limited help for remediation contractors given their current state of digitalisation.

3.3.3.1.2 Land developers

Land developer respondents self-assessed as being 'moderately digital', basing their decisions on digital tools most of the time. Their use of digital tools is generally more dominant during strategic and master planning stages, where reliance on outputs from digital tools is greatest. Their outputs are then refined as the development process progresses. Numerous kinds of data are used, particularly land value data and other infrastructure datasets (e.g., highways, energy), not always used by another brownfield stakeholder who responded to the questionnaire. Environmental datasets are also used to a lesser extent, as environmental constraints and ground conditions are often considered as part of work carried out by third-party consultants or ground investigation specialists which are then used to make professional recommendations back to the developers. One respondent indicated that increased use of GIS is expected in the future with the use of "more GIS-based data" as developers seek to be more digitalised, adopting and integrating digital tools throughout the site development process.

3.3.3.1.3 Local Authority Planning

Local Authority (LA) (Local Government) planners self-assessed as either moderately or very digital, which is aligned with the efforts seen in recent years to modernise and digitise the planning process in England and other parts of the UK (MHCLG, 2018). Despite this, they only base decisions on digital tool outputs in 50% of cases. LA planners mostly use GIS and spreadsheets during all stages before planning consent (Figure 3.1) is granted with some use of WebGIS. In the future, planners are seeking to incorporate a wider variety of datasets into their decision making. Currently, they utilise environmental, infrastructure and planning datasets. Future datasets of interest indicated by respondents might include "deprivation indices", "food growing availability", "greenspace", "heritage", and "active travel datasets". One respondent also commented that they: "would like to see if we can access more public health data that could be tied into prioritising work". This comment may be a reaction to COVID-19, but it does demonstrate that planners and local authorities are looking towards using different and not previously considered datasets to support their decision making. Generating meaningful results from these datasets may be improved with the development of new digital tools.

3.3.3.1.4 Consultants

Consultants were the most digitalised of the stakeholders, with half of the respondents self-assessing as being extremely digital. There is some disparity in the use of digital tools for decision making, with 33% of consultants using digital tools sometimes, 33% half the time and 33% most of the time. Common digital tools used by consultants include spreadsheets, GIS, AutoCAD ™ software, digital fieldwork equipment and 3D modelling software. Additionally, the majority of consultants also commented that HoleBase ™ is used, specifically utilising the ags file format. Ags is a text file format developed by the

Association of Geotechnical and Geo-environmental Specialists (AGS) for the transfer of site investigation data (including borehole positions, soil and rock descriptions, sample depths etc.) (AGS, 2022). Consultants use the largest variety of digital tools of any stakeholder group, and throughout the entire development process, unlike other stakeholder groups. This variety and reliance on digital tools perhaps reflect the range of assessments and services the consultants provide. This could also be because to perform their role they require the use of a broad range of different software tools or that using this range of tools gives them a competitive advantage or helps with communication of findings to their clients. The digital tools and software used during desk studies differ from the kind of tools used during post-site investigation/analysis phases (Figure 3.1). During the post-site investigation phase, specialist software and tools are used such as subsurface 3D modelling or spreadsheet models to statistically analyse contamination concentrations in soil, whereas during desk study, multipurpose digital tools are used such as AutoCAD™ and GIS.

Consultants utilise the widest variety of spatial data (e.g., geoenvironmental, geological, spatial planning, site-investigation locations) in their day-to-day operations, drawing upon a wide range of environmental data types throughout the decision making process. Consultants also commented that having "better digital tools would enable more efficient processing [of data]" and a "clearer presentation [of data]", and that existing systems can compartmentalise their analysis, which is time-consuming. Feedback from consultants suggests that in the future they would look to further "increase the use of GIS" and spatial data for evaluating the ground conditions of sites and creating spatial outputs for their clients.

3.3.3.1.5 Regulatory bodies

Regulators (including the Environment Agencies for England, Scotland, and Wales) self-assessed as being moderately (50%), very (33%), or extremely digital (17%). They use a variety of digital tools to help them make their decisions, including spreadsheets, data visualisation tools, GIS and WebGIS. Regulator respondents also stated that they rely on digital tools for their decision making at least half of the time (17%), most of the time (67%), or always (17%). Regulators utilise different digital tools throughout their operations, for example using GIS tools when deciding whether to place a contaminated land condition on a development or when conducting an initial risk screening and for the development of conceptual site models. Spreadsheets are often used for numerical modelling for risk assessment of chemical contamination. A wide range of digital tools are used for risk assessment, where they offer non-statutory advice to LPAs, land developers, professional advisors, and strategic planners. Regulators also make use of a range of environmental and non-scientific data, including many of the datasets being owned and curated by regulators themselves (i.e., national flood risk datasets). The respondents state that they somewhat agree their existing systems are suitable for their needs, but in the future want to improve their GIS and mapping capabilities.

3.3.3.1.6 Scientific research community

Respondents from the scientific research community self-assess as being either very digital (50%), extremely digital (25%) or, moderately digital (25%), often using digital tools to make decisions with (75% always or more). They utilise a variety of digital tools in their decision making, mainly spreadsheets for the analysis of experimental data, and GIS/WebGIS tools for the spatial visualisation of datasets. Scientific researchers also make use of a wider variety of software programming languages, including Python, R, and MATLAB for developing models or performing data transformations. Generally, the

work of the scientific research community takes place outside of the mainstream brownfield site redevelopment process, but when involved, the scientific research community operates during detailed risk assessment, after intrusive site investigation has taken place. Scientific researchers were reported to make use of a smaller variety of data, mainly chemical and geotechnical testing results.

3.3.3.2 Barriers for brownfield redevelopment

One of the questions within the questionnaire was to score (1–5) the key issues/barriers that hamper or delay brownfield redevelopment (Table 3.2), with 1 being little to no impact and 5 being a major impact.

Table 3.2 A ranking of key brownfield redevelopment issues as determined by stakeholders who responded to the questionnaire.

Rank	Key Issue	Mean Score
1	Remediation costs	4.06
2	Unforeseen ground conditions	4.05
3	Presence of hazardous substances e.g., Asbestos, chemical contamination etc.	3.97
4	Awareness of the brownfield redevelopment process	3.54
5	Land prices	3.54
6	Environmental Constraints	3.48
7	Unit sale prices	3.42
8	Geography and infrastructure (e.g., road links, waste management proximity etc)	3.41
9	Availability of scientific data – below ground	3.40
10	Improper development end-use	3.28

Respondents to the questionnaire collectively ranked remediation costs as the principal issue of concern. Furthermore, one question within the questionnaire was designed to determine explicitly if remediation and ground engineering costs have the biggest impact on a project. Responses to this show that most respondents “Agree” or “Somewhat agree” with the statement. Textual responses also reveal that location is also a major determinant of the economic viability of the site, with stakeholders from all groups mentioning the location.

Figure 3.5 is a word cloud generated from responses recorded in Qualtrics™ when questionnaire respondents were asked about cost drivers for remediation and ground engineering. Developers state that remediation cost is far less important than other areas (i.e., infrastructure costs), in overall economic viability. Within responses to other questions, when asked to identify key issues or barriers to brownfield redevelopment, the most commonly received response was remediation costs. Cost is also frequently stated in the in-text responses, with 39 Nvivo™ instances of "cost" being mentioned. However, when the text was analysed further, developers had stated that the cost and time of remediation could often be "too costly", or that the process "could take longer than expected", whereas consultancies and remediation contractors, identified that "lack of financial planning for remediation costs can cause projects to fail or stagnate".

Figure 3.5 A word cloud generated from the textual responses when stakeholders were asked about cost drivers for remediation and ground engineering.

The second most common factor, after remediation costs, was unforeseen or unplanned ground conditions being encountered. Using quantitative analysis in Nvivo™. There are over 120 references of keywords related to ground conditions and contamination.

Furthermore, other keywords of such as “issues” occur when respondents referred to ground and contamination issues. Text-based responses also provide useful commentary. Local planning officers and consultants state that “unforeseen, and unplanned contamination leads to project overrun and delay 9 times out of 10”. One local planning officer stakeholder and many consultancies stated that “the biggest uncertainties are geotechnical/stability related as opposed to contamination related”. A key difference emerging between stakeholders on this issue is that consultants and planning officers tend to identify ground conditions as key issues, whereas developers, national government, and regulators, do not cite it as a barrier as often, instead stating other issues such as “cultural issues” and “weather”. This may result in the fact that their priority is not specifically focussed on ground issues but the wider development, illustrating the differences in priorities and agendas between stakeholder groups.

Poor project planning, management and logistical difficulties are often stated as leading to project overrun and overspending. This form of feedback arises mostly from consultants and remediation contractors such that it may act on behalf of an overall developer or local authority. Quantification of word occurrence in Nvivo ™ provided evidence for this, where 40 references were recorded for keywords such as “poor planning”, “bad management”, “lack of planning”, or “bad communication”. Consultants and contractors mainly state that poor planning, bad management, lack of awareness of ground conditions and bad time/project management lead to their clients seeking a cheaper or faster investigation leading to bad data, which in turn leads to problems.

Across all stakeholder groups, data was identified as one of the main limiting factors for stakeholder decision making. Figure 3.6 presents a word cloud generated using Nvivo™ centred around the keyword ‘data’. The terms ‘lack” and “poor”, “format” and “quality”

often appear when data is being mentioned. When combined with manual textual analysis, the stakeholder surveyed identified limited access to environmental data and that there is

Figure 3.6 Occurrence of keywords when stakeholders mentioned "data".

poor visualisation of the variety of data they use in their operations. One consultant stakeholder summarised that "[there is] Insufficient data and an inability to adequately identify geotech[nical] and geo-env[ironmental] hazards "and "inadequate data/information on the subsurface, results in poor decisions". To perform their role, they are required to use lots of different software packages and systems. Consultants utilise the widest variety of spatial data in their day-to-day operations, drawing on data from lots of different disciplines to use throughout the decision making process. Questionnaire respondents also commented that having better digital tools would enable more efficient

processing of data and a clearer presentation of it and that existing systems can compartmentalise their analysis, which is time-consuming.

3.3.4 Challenges for brownfield digital tools

Results from the questionnaire indicate that there is still a large disparity between stakeholders. Consultancies, national government, and the scientific research community are the most digitalised brownfield stakeholder groups (Figure 3.4), in contrast, remediation contractors and developers are the least digitally enabled. Not all stakeholders require digital tools to conduct their day-to-day operations, however, the addition of well-designed digital tools is seen to add value and support decision making across the brownfield sector (Bartke and Schwarze, 2015). The uptake of new technologies by large organisations may lead to a trickle-down effect, where once new digital tools are used by early adopters, other organisations will follow.

Many different digital tools and data sources are often used by stakeholders to make decisions. Opportunities for future digital tools may include unifying or integrating data of different types into a unified platform or workflow, thus overcoming the disadvantages of using many different pieces of software to make decisions (Bartke and Schwarze, 2015). Other considerations for future digital developments include: (1) the need for a good degree of interoperability with the range of tools currently used (2) the possibility that future developments in the brownfield digital space may be constrained by the varied functionality of existing digital tools.

Stakeholder comments such as “Current digital systems and data handling are not good enough to fully characterise sites”- Consultant, or “Data management and visualisation could be improved in the sector” – Consultant, were common throughout the questionnaire responses. This indicates a key opportunity for future digital tools and data

handling systems to aid decision-makers in manipulating and visualising existing data that is currently unable to be fully exploited. Across the stakeholder groups, responses indicate that digital tools are often used throughout the brownfield redevelopment process, for specialised tasks. However, the dependency on digital tools for decision making is greatest during the early stage of redevelopment, where sites are being evaluated and investigated. This suggests that digital tools applied in the early stages of decision making may be most useful, fitting into well-established workflows.

Textual responses to the question on future digitalisation plans indicate that there is an expected increased uptake of the use of spatial data (environmental data, spatial planning data, population data, public health data etc) and GIS software across the sector, where not already used, and increased integration of these technologies, where not already commonplace. Because of this, both current and future digital tools, data and decision support systems will need to become interoperable with spatial software and workflows (i.e., web-based spatial analysis and data management). As indicated by the stakeholder comments/feedback throughout Section 3 of the online questionnaire, the adoption of digital tools and data systems will be crucial for improving decision making across the sector. We also identify that the improvement of digital technologies as communication tools has the potential to allow technical stakeholders and experts to engage with peripherally involved stakeholders (Figure 3.2) allowing them to understand a redevelopment option or scenario and contribute their views in a way not previously allowed. However, future developments are not without their challenges (Gebhart et al., 2016). As shown by our questionnaire, stakeholders' interest in the adoption of new technologies is strong (75%). Strong user interest in the testing of new tools should lead to the improvement of tools by developers as they become increasingly tailored to the

stakeholder's needs. This continuous improvement process of stakeholder involvement, user testing and product refinement should lead to an increased embedding of digital tools into the workflows of many brownfield stakeholders, in turn resulting in better decision making.

Stakeholder issues around the quality of data visualisation provide a good mandate for new digital tools, where a large variety of data (environmental, social etc.) can be visualised together, as well as adding value through generated outputs, overcoming existing issues of digital systems identified by stakeholders.

Uncertainty around unforeseen ground conditions constitutes the second most frequently selected issue. Textual analysis of the questionnaire provides evidence that the lack of understanding of ground conditions and the risk associated with ground contamination and instability leads to problems with project/site development. For example, one consultant states that “clients not appreciating the impact of ground risk” have a big impact on project overrun and overspending. However, there are several key differences between stakeholders. Generally, ground conditions are seen as representing a considerable barrier by technical experts (i.e., consultants, remediation contractors etc). In contrast, developers and planners do not consider ground conditions as a significant barrier, indicating issues around risk understanding or risk communication. The various stakeholder groups identify different issues as problematic for brownfield redevelopment depending on their area of specialism. Table 3.3 shows the variability between key stakeholder groups when they were asked to rank key brownfield issues within the questionnaire. The key brownfield issues shown in Table 3.3 are the top ten key issues identified shown in Table 3.2.

Analysis of textual responses indicates that developers and contractors may see economic and time constraints as being the most important, whereas regulators and local governments see risk reduction and regulatory compliance as paramount. It is this difference in perspective that may potentially lead to a lack of understanding of key issues between stakeholders and specialists which in turn can lead to further problems with project management and communication.

Table 3.3 Variability of key brownfield issues between key stakeholder groups.

Stakeholder Group	Key Brownfield Issue (mean score)									
	Availability of scientific data – below ground	Awareness of the brownfield redevelopment process	Environmental Constraints	Geography and infrastructure	Improper development end-use	Land prices	Presence of hazardous substances	Remediation costs	Unforeseen ground conditions	Unit sale prices
Consultant	3.36	3.37	3.45	3.52	3.2	3.39	4.04	4.11	4.23	3.24
Developer	3.25	3.5	3	3	3.33	4.75	3.25	4.5	3.5	4.33
Landowner	3.25	3.5	3.25	3.25	3.25	4.5	3.75	4.25	4.25	4
Local Government	2.8	4	4.25	4.17	3.33	3.29	3.71	3.71	3.57	3.17
National Government	3.33	3.33	2	4.67	4.33	4.33	3.33	4.33	3	4.33
Regulator	3.33	3.83	3.75	2.67	2.83	2.67	4	4.33	4	2.67
Remediation Contractor	4	4.67	3	3.33	3.67	2.33	5	4.33	4.33	3.67
Scientific research community	3.67	3.67	3	2.67	3.5	3.67	4	3.33	4.33	4

3.3.5 Opportunities across the brownfield sector

Across the urban planning and redevelopment sector, many technologies and digital tools are beginning to be adopted and used for a variety of tasks. For example, the use of unmanned aerial vehicles (UAVs) and drones is now commonplace (Geoterra, 2022; Routescene, 2022; Southwest Surveys, 2022). These UAVs and drones can also carry several sensors such as LiDAR for the creation of high-resolution digital elevation models of sites and buildings. To process this raw data, many organisations utilise high-processing power computers and 3D modelling software to produce meaningful outputs for their clients. Once generated, 3D models and scans can be viewed by users in virtual reality or view 'in-situ' by using augmented reality technologies (Oke and Arowoiya, 2021; Safikhani et al., 2022) making it easy for stakeholders to relate what the data is showing to the real world. Similarly, the creation of so-called 'digital twins' for urban areas is now also underway. Digital twins are digital representations of physical things. The Centre for Digital Built Britain (CDBB) is working to create the National Digital Twin programme (NDTp) (CDBB, 2022) which is seeking to create a digital twin for the built environment across the UK. This digital twin will include buildings, infrastructure, and eventually subsurface assets (Cabinet Office and Geospatial Commission, 2021). The NDTp will improve how infrastructure is built, managed, and operated to support planning and development for urban areas. The UK government recently published the UK's Digital Strategy (UK Government, 2022), building on the 'levelling-up' agenda. This policy paper further demonstrates the UK Governments' drive towards digitalisation and adoption of new digital technologies across different sectors (UK Government, 2022).

Across the land development sector in the UK, there is a recognised emphasis being placed on digitalisation for the planning and redevelopment process, as well as access and management of data and geospatial data. For example; the UK government's 2020 White Paper on planning for the future, pushed to increase the digital aspects of the planning system in the UK (MHCLG, 2020), the Geospatial Commission's report on finding geospatial data (Cabinet Office and Geospatial Commission, 2020), as well the publication and promotion of geospatial data standards (Ordnance Survey, 2022) in line with long-standing 'FAIR' principles (GO Fair, 2022) and international standards for geospatial data (ISO, 2020).

These digital initiatives seen in the UK planning and land development sector are also seen in other countries across the world. It is recognised by the European Union Joint Research Centre, that digital technologies will be pivotal in delivering a green and more sustainable Europe in the coming years (EU, 2022) and upskilling digital capabilities across sectors will ensure a sustainable future for people, the economy and society withing Europe (European Commission, 2020). Likewise, the importance of digital tools to support environmental management decision making is also recognised by the US EPA which in recent years has developed many digital tools and data platforms, aligning with the US Foundations for Evidence-based Policymaking Act of 2018 (US Congress, 2018). The development of data-driven tools has been and will continue to be a response to governments and policy but also a reaction to industry requirements allowing organisations to provide a better, high-quality service to their customers, in both the private and public sectors.

Our findings suggest that one area for future digital tools could be in the identification and understanding of problematic ground conditions. This would not only allow

stakeholders to plan for these unforeseen ground conditions but also communicate the risk to other stakeholders. For example, certain stakeholders or other interested parties may not fully understand the extent or nature of a contamination problem. By using modern digital visualisation tools, a consultant or planner may be able to communicate the problem and potential impacts on the development and plan. For example, 3D virtual reality software could be used to visualise the extent of a contamination plume in the subsurface, allowing an increased understanding and appreciation of the scale, nature, and consequences of the contamination. The foundation for tools of this nature is already present within the academic literature (Bartke et al., 2016; Hammond et al., 2021; Huysegoms and Cappuyns, 2017; Morio et al., 2013). One regulator who responded to the questionnaire states that "Lack of communication between developers, planning teams and contaminated land consultants" represents the biggest cause of project overrun and overspending. By manipulating existing data and workflows, through new data visualisation and modelling, digital tools and DSSs may help stakeholders (including informed stakeholders (Figure 3.2)), to better understand and communicate options and scenarios during project/development planning. Across all stakeholder types, development and risk mitigation costs, and the understanding of these costs, were by far the most important factor in the success or failure of a project. New digital tools and data systems have the potential to greatly improve how these risks/costs are quantified, presented, and understood. For example, as outlined by Hammond et al. (2021), improved user interfaces/user experience, the use of WebGIS, and the adoption of innovative geospatial and machine learning techniques. If these tools and data systems utilise the abundance of open environmental and geoscientific spatial datasets, there could be significant potential to improve our ability to model and visualise important issues.

Insights from stakeholder engagement often lead to the establishment of guidance and frameworks for future DSS research, namely the international research by Bartke et al. (2016), Moya et al. (2019), and Pizzol et al. (2016). However, these frameworks and guidance are often created for individual tool or system development. Here we present seven core principles for all future digital brownfield tools. These have been derived from specific insights produced from this stakeholder consultation study. Future brownfield digital tools should be: (1) Stakeholder driven – understanding and incorporating stakeholder preference remains key to tool development; (2) Problem centred – digital solutions should be created to respond to direct end-user need; (3) Visual – to engage a wide variety of stakeholders outputs from digital tools should utilise modern visualisation and graphical capabilities; (4) Intuitive – for ease of use tools should include intuitive functions and user experience (5) Interactive – enhance engagement from the end-user through interactivity and user participation; (6) Interoperable – there already exists numerous helpful digital tools, future developments should seek to align with or enhance these; (7) Geospatial data-driven – more and more decisions are being supported through with geospatial evidence and the uptake of geospatial methods is expected to continue to increase across the sector.

3.4 Conclusions

This paper has presented key insights from a stakeholder consultation on the potential that future development of digital tools and data systems will have on the brownfield sector. Our findings show that different stakeholder groups within the UK brownfield sector are at various stages of digitalisation. Digital tools and the uptake of new technologies have a great impact on how brownfield professionals currently work and will work in the future. Recent policy and guidance, as well as developments in the private

and research sectors, are driving the creation and adoption of new digital tools in the UK, Europe, and across the world. As the development and uptake of new technologies continue, future policies and practices will be shaped to reflect the role digital technologies play in supporting decision makers. There are three key areas of brownfield redevelopment identified by this study where digital tools will have the biggest impact: (1) Supporting discussion around land-use planning, (2) Understanding of ground conditions and communication of the associated risk, and (3) Demystifying and quantifying economic factors related to developing brownfield land. Well-designed digital tools have the potential to revolutionise how the brownfield sector understands and communicates key issues leading to better decision making and more sustainable brownfield redevelopment.

3.5 Author contributions

E. Hammond: Conceptualization, Methodology, Analysis, Investigation, Writing – original draft, Visualisation, Data curation. **D. Beriro, F. Coulon, S. Hallett**: Project administration, Conceptualization, Validation, Analysis, Resources, Writing-Review and Editing, Supervision, Funding acquisition. **R. Thomas, D. Hardy**: Writing – review & editing.

3.6 References

Alexandrescu, F., Klusáček, P., Bartke, S., Osman, R., Frantál, B., Martinát, S., Kunc, J., Pizzol, L., Zabeo, A., Giubilato, E., Critto, A., Bleicher, A., 2017. Actor networks and the construction of applicable knowledge: the case of the Timbre Brownfield Prioritization Tool. Clean Technol. Environ. Policy 19, 1323–1334. https://doi.org/10.1007/s10098-016-1331-8

Ameller, J., Rinaudo, J.D., Merly, C., 2020. The Contribution of Economic Science to Brownfield Redevelopment: A Review. Integr. Environ. Assess. Manag. 16, 184–196. https://doi.org/10.1002/ieam.4233

Association of Geotechnical and Geoenvironmental Specialists, 2022. AGS Data Format [WWW Document]. URL https://www.ags.org.uk/data-format/ (accessed 1.31.22).

Balogun, A.L., Marks, D., Sharma, R., Shekhar, H., Balmes, C., Maheng, D., Arshad, A., Salehi, P., 2020. Assessing the Potentials of Digitalization as a Tool for Climate Change Adaptation and Sustainable Development in Urban Centres. Sustain. Cities Soc. 53. https://doi.org/10.1016/J.SCS.2019.101888

Bartke, S., Martinát, S., Klusáček, P., Pizzol, L., Alexandrescu, F., Frantál, B., Critto, A., Zabeo, A., 2016. Targeted selection of brownfields from portfolios for sustainable regeneration: User experiences from five cases testing the Timbre Brownfield Prioritization Tool. J. Environ. Manage. 184, 94-107. https://doi.org/10.1016/j.jenvman.2016.07.037

Bartke, S., Schwarze, R., 2015. No perfect tools: Trade-offs of sustainability principles and user requirements in designing support tools for land-use decisions between greenfields and brownfields. J. Environ. Manage. 153, 11–24. https://doi.org/10.1016/j.jenvman.2015.01.040

Bentley Systems, 2021a. HoleBASE - Geotechnical data management software for boreholes and lab [WWW Document]. URL https://www.bentley.com/en/products/product-line/geotechnical-engineering-software/holebase (accessed 8.17.21).

Bentley Systems, 2021b. gINT - Geotechnical and Geoenvironmental Software [WWW Document]. URL https://www.bentley.com/en/products/brands/gint (accessed 8.17.21).

Beriro, D., Nathanail, J., Salazar, J., Kingdon, A., Marchant, A., Richardson, S., Gillet, A., Rautenberg, S., Hammond, E., Beardmore, J., Moore, T., Angus, P., Waldron, J., Rodrigues, L., Nathanail, P., 2022. A decision support system to assess the feasibility of onshore renewable energy infrastructure. Renew. Sustain. Energy Rev. 168, 112771. https://doi.org/10.1016/J.RSER.2022.112771

Billger, M., Thuvander, L., Wästberg, B.S., 2017. In search of visualization challenges: The development and implementation of visualization tools for supporting dialogue in urban planning processes. Environ. Plan. B Urban Anal. City Sci. 44, 1012–1035. https://doi.org/10.1177/0265813516657341

CABERNET, 2006. Sustainable Brownfield regeneration: CABERNET network report. University of Nottingham Land quality management report.

Cabinet Office, Geospatial Commission, 2021. National Underground Asset Register (NUAR) [WWW Document]. URL https://www.gov.uk/government/collections/national-underground-asset-register-nuar (accessed 2.2.22).

Cabinet Office, Geospatial Commission, 2020. Finding Geospatial Data [WWW Document]. URL https://www.gov.uk/government/publications/finding-geospatial-data/finding-geospatial-data (accessed 2.2.22).

Cappai, F., Forgues, D., Glaus, M., 2019. A Methodological Approach for Evaluating Brownfield Redevelopment Projects. Urban Sci. 2019, Vol. 3, Page 45 3, 45. https://doi.org/10.3390/URBANSCI3020045

Centre for Digital Built Britain, 2022. National Digital Twin Programme | Centre for Digital Built Britain [WWW Document]. URL https://www.cdbb.cam.ac.uk/what-we-do/national-digital-twin-programme (accessed 2.2.22).

CL: AIRE, 2022. CL: AIRE Website [WWW Document]. URL https://www.claire.co.uk/ (accessed 1.31.22).

CL: AIRE, 2020. Professional Guidance: Comparing Soil Contamination Data with avCritical Concentration. Buckinghamshire.

Connaughton, J., Mbugua, L., 2008. Faster Building for Industry: NEDO (1983), in: Construction Reports 1944–98. John Wiley & Sons, Ltd, pp. 114–129. https://doi.org/10.1002/9780470758526.ch9

CPRE, 2020. Recycling our land: the state of brownfield 2020 - An updated analysis of the potential of brownfield land for new homes.

Drenning, P., Chowdhury, S., Volchko, Y., Rosén, L., Andersson-Sköld, Y., Norrman, J., 2022. A risk management framework for Gentle Remediation Options (GRO). Sci. Total Environ. 802, 149880. https://doi.org/10.1016/J.SCITOTENV.2021.149880

Environment Analyst, 2021. Brownfield Awards 2021 [WWW Document]. URL https://www.brownfield-awards.environment-analyst.com/ (accessed 11.10.21).

EU JRC, 2022. 5 digital solutions for a greener Europe [WWW Document]. URL https://joint-research-centre.ec.europa.eu/jrc-news/5-digital-solutions-greener-europe-2022-07-05_en (accessed 8.22.22).

European Commission, 2022. Smart cities [WWW Document]. URL https://ec.europa.eu/info/es-regionu-ir-miestu-pletra/temos/miestai-ir-miestu-pletra/miestu-iniciatyvos/smart-cities_en (accessed 8.23.22).

European Commission, 2020. Shaping Europe's Digital Future. Luxembourg. https://doi.org/10.2759/48191

Ferrari, G., Ai, P., Marinello, F., Pezzuolo, A., 2022. Where and how? A comprehensive review of multicriteria approaches for bioenergy plant siting. J. Clean. Prod. 346. https://doi.org/10.1016/j.jclepro.2022.131238

Gebhart, M., Giessler, P., Abeck, S., 2016. Challenges of the Digital Transformation in Software Engineering, in: ICSEA 2016.

Geoterra, 2022. UAV Aerial LiDAR Surveys [WWW Document]. URL https://www.geoterra.co.uk/services/surveying-services/uav-aerial-lidar-surveys/ (accessed 2.2.22).

GO Fair, 2022. FAIR Principles [WWW Document]. URL https://www.go-fair.org/fair-principles/ (accessed 2.2.22).

Guarini, M.R., Battisti, F., Chiovitti, A., 2018. A methodology for the selection of multi-criteria decision analysis methods in real estate and land management processes. Sustainability 10 (2), 507. https://doi.org/10.3390/su10020507

Hammond, E.B., Coulon, F., Hallett, S.H., Thomas, R., Hardy, D., Kingdon, A., Beriro, D.J., 2021. A critical review of decision support systems for brownfield redevelopment. Sci. Total Environ. 785, 147132. https://doi.org/10.1016/j.scitotenv.2021.147132

Huysegoms, L., Cappuyns, V., 2017. Critical review of decision support tools for sustainability assessment of site remediation options. J. Environ. Manage. 196, 278-296. https://doi.org/10.1016/j.jenvman.2017.03.002

Huysegoms, L., Rousseau, S., Cappuyns, V., 2019. Indicator use in soil remediation investments: Views from policy, research and practice. Ecol. Indic. 103, 70–82. https://doi.org/10.1016/j.ecolind.2019.03.048

Interaction Design Foundation, 2022. What is Design Thinking? [WWW Document]. URL https://www.interaction-design.org/literature/topics/design-thinking (accessed 3.17.22).

International Organization for Standardization, 2020. ISO - ISO 19115-1:2014/Amd 2:2020 - Geographic information — Metadata — Part 1: Fundamentals — Amendment 2 [WWW Document]. URL https://www.iso.org/standard/80275.html (accessed 9.12.22).

JISCMail, 2022. JISCMail - CONTAMINATED-LAND-STRATEGIES List at WWW.JISCMAIL.AC.UK [WWW Document]. URL https://www.jiscmail.ac.uk/cgi-bin/webadmin?A0=CONTAMINATED-LAND-STRATEGIES (accessed 1.31.22).

Leonidou, E., Christofi, M., Vrontis, D., Thrassou, A., 2020. An integrative framework of stakeholder engagement for innovation management and entrepreneurship development. J. Bus. Res. 119, 245–258. https://doi.org/10.1016/j.jbusres.2018.11.054

Longhurst, R., 2016. Semi-structured Interviews and Focus Groups, in: Key Methods in Geography. SAGE, p. 103.

Loures, L., Vaz, E., 2018. Exploring expert perception towards brownfield redevelopment benefits according to their typology. Habitat Int. 72, 66–76. https://doi.org/10.1016/j.habitatint.2016.11.003

Male, S., 2008. Faster Building for Commerce: NEDO (1988), in: Construction Reports 1944–98. John Wiley & Sons, Ltd, pp. 130–144. https://doi.org/10.1002/9780470758526.ch10

Ministry of Housing Communities & Local Government, 2020. Planning for the Future. London.

Ministry of Housing Communities and Local Government, 2019. National Planning Policy Framework. Her Majesty's Stationery Office, London.

Ministry of Housing Communities and Local Government, 2018. High digital ambitions for our policy department [WWW Document]. URL https://mhclgdigital.blog.gov.uk/2018/06/11/high-digital-ambitions-for-our-policy-department/

Ministry of Housing Communities and Local Government, 2017. Brownfield registers and permission in principle: frequently asked questions [WWW Document]. URL https://www.gov.uk/government/publications/brownfield-registers-and-permission-in-principle/brownfield-registers-and-permission-in-principle-frequently-asked-questions (accessed 2.5.20).

Morgan, D.L., 1996. Focus Groups. Annu. Rev. Sociol. 22, 129–152. https://doi.org/10.1146/annurev.soc.22.1.129

Morio, M., Schädler, S., Finkel, M., 2013. Applying a multi-criteria genetic algorithm framework for brownfield reuse optimization: Improving redevelopment options based on stakeholder preferences. J. Environ. Manage. 130, 331–346. https://doi.org/10.1016/j.jenvman.2013.09.002

Moya, B., Parker, A., Sakrabani, R., 2019. Challenges to the use of fertilisers derived from human excreta: The case of vegetable exports from Kenya to Europe and influence of certification systems. Food Policy 85, 72–78. https://doi.org/10.1016/j.foodpol.2019.05.001

Naidu, R., Biswas, B., Willett, I.R., Cribb, J., Kumar Singh, B., Paul Nathanail, C., Coulon, F., Semple, K.T., Jones, K.C., Barclay, A., John Aitken, R., 2021. Chemical pollution: A growing peril and potential catastrophic risk to humanity. Environ. Int. 156, 106616. https://doi.org/10.1016/j.envint.2021.106616

Nogués, S., Arroyo, N.L., 2016. Alternative approach to prioritization of brownfield reclamation attending to urban development potentialities: Case study in a depressed industrial district in Northern Spain. J. Urban Plan. Dev. 142, 5015002. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000272

Office of Government Property, Local Government Association, Ministry of Housing Communities and Local Government, 2021. One Public Estate: Brownfield Land Release Fund April 2021 | Local Government Association [WWW Document]. URL https://www.local.gov.uk/ope-brownfield-land-release-fund (accessed 1.31.22).

Oke, A.E., Arowoiya, V.A., 2021. An analysis of the application areas of augmented reality technology in the construction industry. Smart Sustain. Built Environ. ahead-of-p. https://doi.org/10.1108/SASBE-11-2020-0162

Ordnance Survey, 2022. Why geospatial data standards matter [WWW Document]. URL https://www.ordnancesurvey.co.uk/newsroom/insights/why-do-geospatial-data-standards-matter (accessed 2.2.22).

Pizzol, L., Zabeo, A., Klusáček, P., Giubilato, E., Critto, A., Frantál, B., Martinát, S., Kunc, J., Osman, R., Bartke, S., 2016. Timbre Brownfield Prioritization Tool to support effective brownfield regeneration. J. Environ. Manage. 166, 178–192. https://doi.org/10.1016/j.jenvman.2015.09.030

QSR, 2021. Qualitative Data Analysis Software | NVivo [WWW Document]. URL https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home (accessed 4.13.21).

Qualtrics, 2021. Qualtrics XM [WWW Document]. URL https://www.qualtrics.com/uk/?rid=ip&prevsite=en&newsite=uk&geo=GB&geomatch=uk (accessed 4.13.21).

Rizzo, E., Pesce, M., Pizzol, L., Alexandrescu., F.M., Giubilato, E., Critto, A., Marcomini, A., Bartke, S., 2015. Brownfield regeneration in Europe: Identifying stakeholder perceptions, concerns, attitudes and information needs. Land use policy 48, 437–453. https://doi.org/10.1016/j.landusepol.2015.06.012

Routescene, 2022. Survey and mapping - UAV LiDAR [WWW Document]. URL https://www.routescene.com/applications/survey-and-mapping/ (accessed 2.2.22).

Ruiz, M.C., Romero, E., Pérez, M.A., Fernández, I., 2012. Development and application of a multi-criteria spatial decision support system for planning sustainable industrial areas

in Northern Spain. Autom. Constr. 22, 320–333. https://doi.org/10.1016/J.AUTCON.2011.09.009

Rylatt, M., Gadsden, S., Lomas, K., 2001. GIS-based decision support for solar energy planning in urban environments. Comput. Environ. Urban Syst. 25, 579–603. https://doi.org/10.1016/S0198-9715(00)00032-6

Safikhani, S., Keller, S., Schweiger, G., Pirker, J., 2022. Immersive virtual reality for extending the potential of building information modeling in architecture, engineering, and construction sector: systematic review. https://doi.org/10.1080/17538947.2022.2038291 15, 503–526. https://doi.org/10.1080/17538947.2022.2038291

Schloemer, S., Furche, M., Dumke, I., Poggenburg, J., Bahr, A., Seeger, C., Vidal, A., Faber, E., 2013. A review of continuous soil gas monitoring related to CCS – Technical advances and lessons learned. Appl. Geochemistry 30, 148–160. https://doi.org/10.1016/J.APGEOCHEM.2012.08.002

Simonofski, A., Vallé, T., Serral, E., Wautelet, Y., 2021. Investigating context factors in citizen participation strategies: A comparative analysis of Swedish and Belgian smart cities. Int. J. Inf. Manage. 56, 102011. https://doi.org/10.1016/J.IJINFOMGT.2019.09.007

SoBRA, 2022. SoBRA Website [WWW Document]. URL https://sobra.org.uk/ (accessed 1.31.22).

Song, Y., Hou, D., Zhang, J., O'Connor, D., Li, G., Gu, Q., Li, S., Liu, P., 2018. Environmental and socio-economic sustainability appraisal of contaminated land remediation strategies: A case study at a mega-site in China. Sci. Total Environ. 610–611, 391–401. https://doi.org/10.1016/J.SCITOTENV.2017.08.016

Southwest Surveys, 2022. Mobile Mapping & LiDAR [WWW Document]. URL https://www.southwestsurveys.co.uk/mobile-mapping-aerial-lidar/ (accessed 2.2.22).

Stratigea, A., Papadopoulou, C.A., Panagiotopoulou, M., 2015. Tools and Technologies for Planning the Development of Smart Cities. J. Urban Technol. 22, 43–62. https://doi.org/10.1080/10630732.2015.1018725

UK Government, 2022. UK's Digital Strategy [WWW Document]. URL https://www.gov.uk/government/publications/uks-digital-strategy (accessed 9.2.22).

US Congress, 2018. Foundations for Evidence-Based Policymaking Act of 2018.

US EPA, 2019. Community Actions that Drive Brownfields Redevelopment. Washington DC.

Velimirovic, M., Bianco, C., Ferrantello, N., Tosco, T., Casasso, A., Sethi, R., Schmid, D., Wagner, S., Miyajima, K., Klaas, N., Meckenstock, R.U., von der Kammer, F., Hofmann, T., 2020. A Large-Scale 3D Study on Transport of Humic Acid-Coated Goethite Nanoparticles for Aquifer Remediation. Water 2020, Vol. 12, Page 1207 12, 1207. https://doi.org/10.3390/W12041207

Wang, H., Shen, Q., Tang, B., 2015. GIS-Based Framework for Supporting Land Use Planning in Urban Renewal: Case Study in Hong Kong. J. Urban Plan. Dev. 141, 05014015. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000216

Washbourne, C.L., Goddard, M.A., Le Provost, G., Manning, D.A.C., Manning, P., 2020. Trade-offs and synergies in the ecosystem service demand of urban brownfield stakeholders. Ecosyst. Serv. 42, 101074. https://doi.org/10.1016/j.ecoser.2020.101074

Wilson, A., Tewdwr-Jones, M., 2021. Digital participatory planning: citizen engagement, democracy, and design, 1st Ed. ed. Routledge.

3.7 Appendix

Table 3.4 Typical stakeholder personas established from key stakeholder interviews.

<table>
<tr><th colspan="2">Typical Stakeholder Personas</th></tr>
<tr><td colspan="2">Consultant 1</td></tr>
<tr><td>Role
Large multi-national multi-discipline consultancy
Provide services for the built and natural environment.
Provides comprehensive ground risk management services from initial site characterisation and investigation (SI) through to remediation management.
Clients
National government
Public agencies
Large land developers
Oil & gas sector
Current digital capabilities
Digital capture system for fieldwork for site investigation work, with data from this being stored on corporate geodatabase system for subsequent use in carrying out analysis and risk assessment.
Open data GIS to assist with desk studies and SI design across the company.</td><td>Digital Challenges
Different SI project management approaches often result in inconsistencies in the quality and completeness of the data.
Similarly, data from previous works are often disparate, being held in a non-structured manner within the central system.
Future of digital
Internal digital architecture changes
Hyperspectral UAV surveys
Automated desk studies
Machine learning (e.g., within flood risk).
Digital Environmental Impact Assessments (EIAs)
Top Brownfield issues
Brownfields cost more to develop
Programme often overruns
Suitability of proposed development
Failure to accurately estimate costs throughout the program
Poor transport links
Access to a site</td></tr>
</table>

<table>
<tr><td colspan="2">Consultant 2</td></tr>
<tr><td>Role
Small independent consultancy
Ground investigation Specialist
Contamination and Geotechnical Specialist
Environmental Services.
Clients
Local Authorities
Small land developers
Current digital capabilities
Moderately digitalised
GIS
Excel
AutoCAD</td><td>Digital Challenges
Cost of digital software and licensing
Future of digital
3D Modelling Software
Top Brownfield issues
Increased Uncertainty and Risk
Extended program
High preliminary costs
Unforeseen ground conditions leading to increased costs</td></tr>
<tr><td colspan="2">Scientific Researcher</td></tr>
<tr><td>Role
Conduct geoscience research (Brownfield Redevelopment)
Provide innovative solutions for clients
Geospatial data modelling
Data generation
Clients
National Government
Regional and Local Authorities
Public Sector Agencies
Current digital capabilities
Very digitalised
GIS
Programming languages
3D Modelling Software
Bespoke geoscience software</td><td>Digital Challenges
Novel integration of data/software
Improved visualisation of data
Future of digital
Predictive modelling/Machine Learning
Top Brownfield issues
Many stakeholders involved
Planning and development process
Access to quality data</td></tr>
</table>

<table>
<tr><td colspan="2">Data Specialist</td></tr>
<tr><td>Role
Data providers
Environmental data reports
Automatic/supervised site appraisal desk studies
Clients
Land Developers (All scales)
Homebuyers
Legal Sector
Public Sector Agencies
Current digital capabilities
Highly digital
GIS
WebGIS
Programming Languages</td><td>Digital Challenges
Conflicting data standards
Manual intervention in the data processing
Future of digital
Predictive modelling
Top Brownfield issues
Understanding of ground conditions
Communication of data uncertainty</td></tr>
<tr><td colspan="2">Remediation Contractor</td></tr>
<tr><td>Role
National brownfield remediation contractor
Enabling works
Remediation works
Clients
National Government
Local Authorities
Large Land Developers
National Infrastructure Projects
Current digital capabilities
AutoCAD
Excel/Statistical Models</td><td>Digital Challenges
Digital skills
Data Interoperability
Future of digital
GIS Software
3D Modelling
Top Brownfield issues
Often overrun and cost more than expected.
Lots of stakeholders involved
Regulation and legislation difficulties</td></tr>
</table>

Table 3.5 All questionnaire responses.

This table presents all 150 responses to the questionnaire. Each response is recorded on a separate row, and each question and sub-question is recorded in each column.

Please see the supplementary material of Hammond et al (2023)

"Appendix A. Supplementary data, Multimedia component 1"

https://ars.els-cdn.com/content/image/1-s2.0-S0301479722019661-mmc1.xlsx

Table 3.6 Summary of questionnaire respondent profiles.

	Percentage	**Count**
Scale of Projects		
International Projects	6%	10
National Projects	24%	43
Regional Projects	33%	60
Local Projects	38%	68
Level of Seniority		
Director Level	10%	12
Associate Director Level	16%	19
Senior Level	36%	42
Intermediate Level	20%	24
Primary Level	9%	11
Not Applicable	4%	5
Other	4%	5
Qualification level		
Doctorate	12%	14
Masters	59%	70
Bachelors	25%	29
Other	4%	5
Professional Experience		
More than 15 Years	48%	57
10 – 15 years	23%	27
5 – 10 years	16%	19
Less than 5 years	13%	15

3.7.1 Blank key stakeholder interview questions

1) Can you tell me about what your particular part of your organisation does? Where do you see this going over the next 5 years?
2) Who do you work for? / Who are your clients / Key stakeholders?
3) How digitised is your organisation? What technologies, digital tools and digital workflow do you use?
4) How does this technology/digital tools support your decision making? What questions do you ask of the data?
5) What are the challenges that come with your current systems and digital tools?
6) Doing digital differently - What would you do differently? Planning to do differently?
7) In your experience, what are the key drivers for brownfield redevelopment vs Greenfield redevelopment?
8) What is the biggest cause of brownfield project failure?
9) Is housing/residential the number #1 priority for brownfield land (with your clients, developers, etc)?

3.7.2 Blank online questionnaire questions

Please see the supplementary material of Hammond et al (2023)

"Appendix A. Supplementary data, Multimedia component 3"

https://ars.els-cdn.com/content/image/1-s2.0-S0301479722019661-mmc3.docx

4 THE DEVELOPMENT OF A NOVEL DECISION SUPPORT SYSTEM FOR REGIONAL LAND USE PLANNING FOR BROWNFIELD LAND.

Ellis B. Hammond[1, 2], Frederic Coulon[2], Stephen H. Hallett[2], Russell Thomas[3], Alistair Dick[4,] Drew Hardy[5], Mark Dickens[6], Emma Washbourn[6], Darren J. Beriro[1*].

[1]British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK.

[2]School of Water, Energy and Environment, Cranfield University, Cranfield, MK43 0AL, UK.

[3]WSP, Kings Orchard, 1 Queen St, Bristol, BS2 0HQ, UK.

[4]Groundsure, Sovereign House, Church Street, Brighton BN1 1UJ, UK

[5]LandTech, 9 Appold St, London EC2A 2AP, UK

[6]Liverpool City Region Combined Authority, 1 Mann Island, Liverpool, L3 1BP, UK.

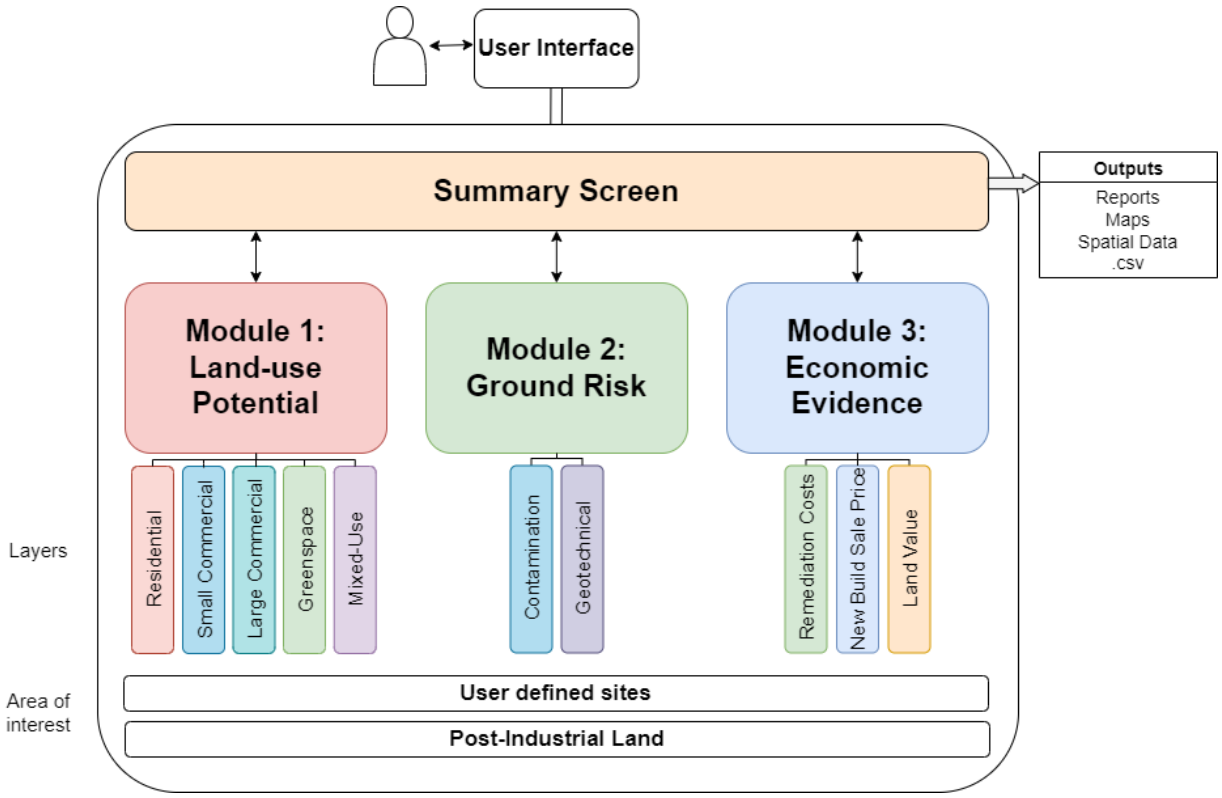
Abstract:

Digital tools, particularly specialised decision support systems (DSSs), are utilised to assist in the complex process of brownfield redevelopment. 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 development and 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, and (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 utilised to implement iterative improvements to the DSS and to plan future developments for the prototype DSS.

Keywords: Brownfield Redevelopment, Digital Tools, Stakeholder Engagement, GIS, MCDA, Land Use, Viability, Risk

Graphical Abstract:



4.1 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 underutilised (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 recognised, 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 Strategic Plan for 2018/19-2022/23 (Homes England, 2018) 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; OGP, LGA, MHCLG, 2021).

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 social, 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 considerations, 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., 2023a). 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.

Informative digital tools can support stakeholders in the decision making process pertaining to redeveloping brownfield land (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 & 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 improves decision making users' 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 presents information and may include some data analysis; and (2) model-based, which typically incorporates 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., 2015, 2013; 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 focusing on other applications, such as modelling groundwater contamination risk or estimating remediation costs for sites.

Numerous DSSs have been developed and successful case studies have been demonstrated in the literature (Hammond et al., 2021) however, the regular use, uptake, and implementation of DSSs in the day-to-day operations of brownfield redevelopment

stakeholders remain low (Ameller et al., 2020; Hammond et al., 2021). Hammond et al. (2021) further reported several limitations of existing brownfield DSS research. Firstly, the majority of prior research primarily focuses on site-specific brownfield decision making problems that arise later in the planning and development process, after detailed intrusive site investigation and remediation technology selection. Secondly, the brownfield DSSs reviewed often underrepresent socioeconomic considerations, as the primary focus is on the environmental and contamination aspects of redevelopment. In cases where socioeconomic criteria are present, they lack detail in their generation or are simply attributed to expert valuation. Thirdly, the scope of stakeholder engagement in existing research is narrow and there is a need to widen it to assess a greater variety of issues and include input from a wider variety of stakeholders. Finally, existing DSSs are typically not designed in a user-led or stakeholder driven manner, resulting in poor user interface and user experience.

This paper aims to improve upon existing research and present a novel DSS development approach. The DSS is designed to aid decision-makers during the early-stages of planning and the redevelopment of brownfield sites at a city-region scale.

4.2 Methods

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

The DSS development was informed by end-user insights from the Liverpool City Region Combined Authority (LCRCA). The Liverpool city region was also 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) 2,783 brownfield sites (6,185.3 ha) identified during a strategic land assessment, and (3) 16 future housing sites (1,159 ha) and 8 future employment sites (1,033 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 <1 ha in size 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., 2023b).

The methods presented in this paper describe the general procedure used to create the DSS outputs for a given area. The results presented in this paper described 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 case-study application to the Liverpool City Region and verification of DSS outputs are reported in Hammond et al. (2023b) (Chapter 5).

4.2.1 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., 2023a). The development approach for DSS

should be stakeholder-driven, problem-centred, visual, intuitive, interactive, interoperable, and geospatial data-driven (Hammond et al., 2023a). 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 (the quality of being easy for people who are not subject-matter experts to use or understand) and align it with their needs. The DSS aims 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, identifying users and their unique goals and challenges, 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), five problem statements were defined, as follows:

1. Difficulty in accessing and understanding spatial data for brownfield redevelopment, hindering knowledge exchange between expert and non-expert stakeholders.
2. Varied GIS capabilities within local/regional governments, with some stakeholders having difficulty utilising 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 a city region government, the *Liverpool City Region Combined Authority* (LCRCA), who are likely to benefit from the DSS were identified. Through semi-structured discussions with these stakeholders, three 'user personas' were created (Figure 4.1), 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 4.1).

Table 4.1 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, regional governments must 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 an 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 utilised and understood by stakeholders with different levels of digital abilities.

Strategic Land-Use Planner

Role

- Lead Spatial Planning Officer responsible for all areas of spatial planning
- Preparing the strategic plan for the region area
- Lead officer for public sector land assets

Goals

- Ensure sustainable planning and development across the area
- Implement spatial planning strategy concepts into planning decisions

Challenges

- Housing is the focus of developers
- Need evidence-base to encourage sustainable place making
- Limited use of spatial data tools for data visualisation

Digital Skills

1 2 **3** 4 5

MS Office | Spreadsheets | GIS
Digital engagement tools

Brownfield Regeneration Officer

Role

- Lead officer for housing partnerships.
- Managing grants and funding delivery.
- Working with consultancies for the development of small sites

Goals

- 'Unlock' brownfield sites by assuring economic viability, site suitability, overall feasibility of development
- Work with developers, planners, and funders to ensure housing supply is met

Challenges

- Accessing data for Economic viability assessment is time consuming
- Not all stakeholder involved understand viability
- Digital technologies not up to task of communicating challenges

Digital Skills

1 2 **3** 4 5

MS Office | Spreadsheets | Digital engagement tools

Digital Spatial Planning Officer

Role

- Lead officer for digital (GIS) spatial planning
- Working with local governments to develop their GIS data and digital local plans
- Managing spatial data ingestion, analysis, visualisation, and access

Goals

- Support land-use planning and planning strategy implementation through GIS and spatial data
- Facilitate the creation and sharing of local authorities digital (GIS) local plans

Challenges

- Access and findability of relevant geospatial data
- Limited digital capabilities within regional government planning team
- Lack of knowledge and confidence with GIS systems local and regional government

Digital Skills

1 2 3 4 **5**

MS Office | Spreadsheets | GIS
WebGIS

Figure 4.1 User personas for the DSS use-case, digital skills range from 1 (least skilled) to 5 (highly skilled)..

4.2.2 User Defined Sites and Post-Industrial Land

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. Post-Industrial Land (PIL) was generated in GIS, using historical land use data to identify previously developed land.

4.2.3 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 the methodology and geoprocessing steps taken to transform, process, and integrate data for the DSS is presented in Figure 4.2. The DSS comprises of the following modules:

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 4.2 refers to factors that determine land use potential, weighting reflects their degree of influence, and criteria 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 (Groundsure, 2023).

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 the identification of areas of interest during the initial screening of land use potential ground risk.

4.2.4 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. Figure 4.3 provides an overview of the approach used to create the land use potential outputs for the DSS. 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 4.2, 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 of chosen criteria with justification refer to Table 4.4 (Appendix 4.8).

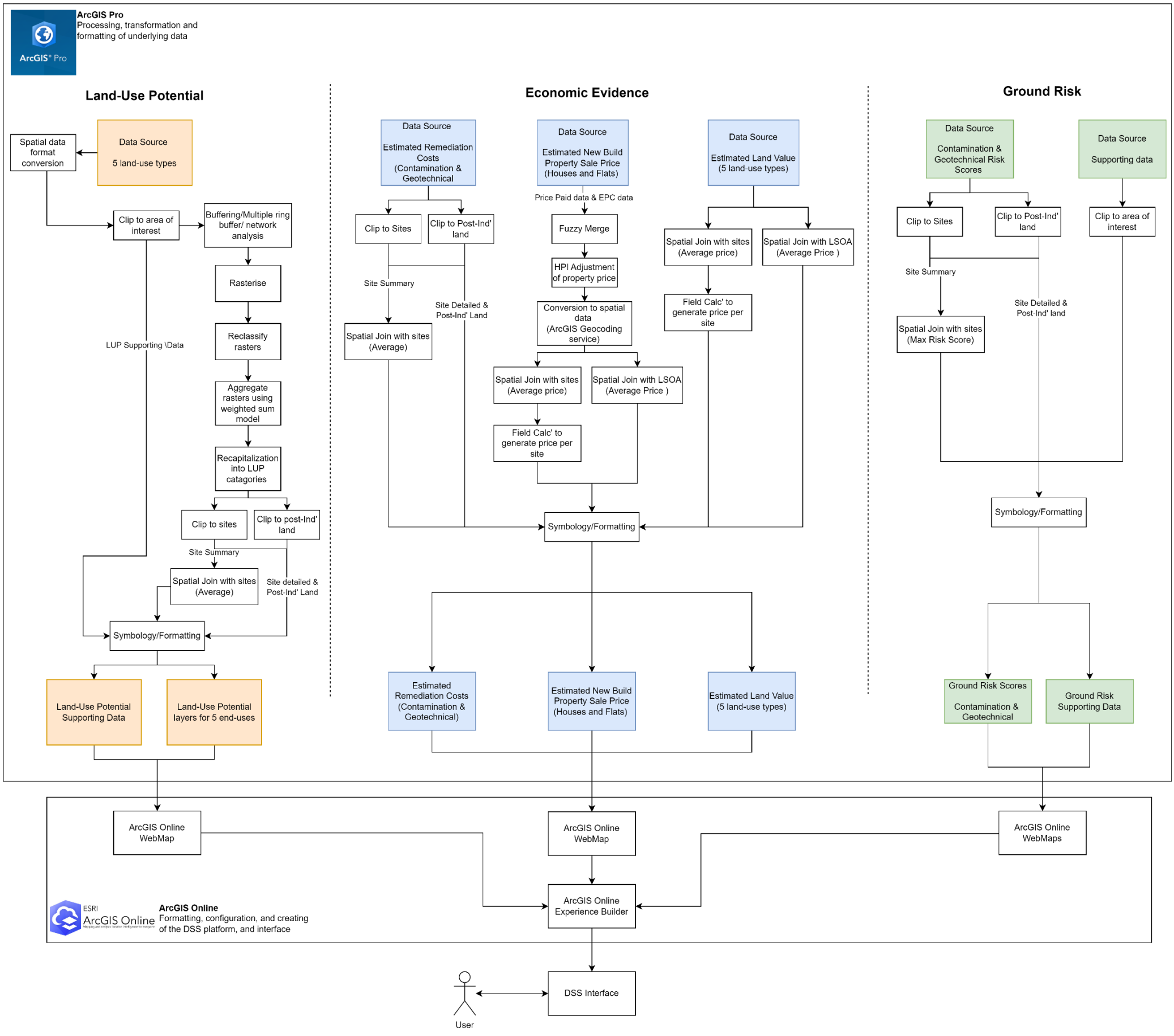


Figure 4.2 Summary of methodology and steps taken to transform, process, and integrate data for the DSS.

To ensure the weightings were representative of the priorities and opinions of decision-makers, findings of critical review work 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 model was developed for each land use potential end-use

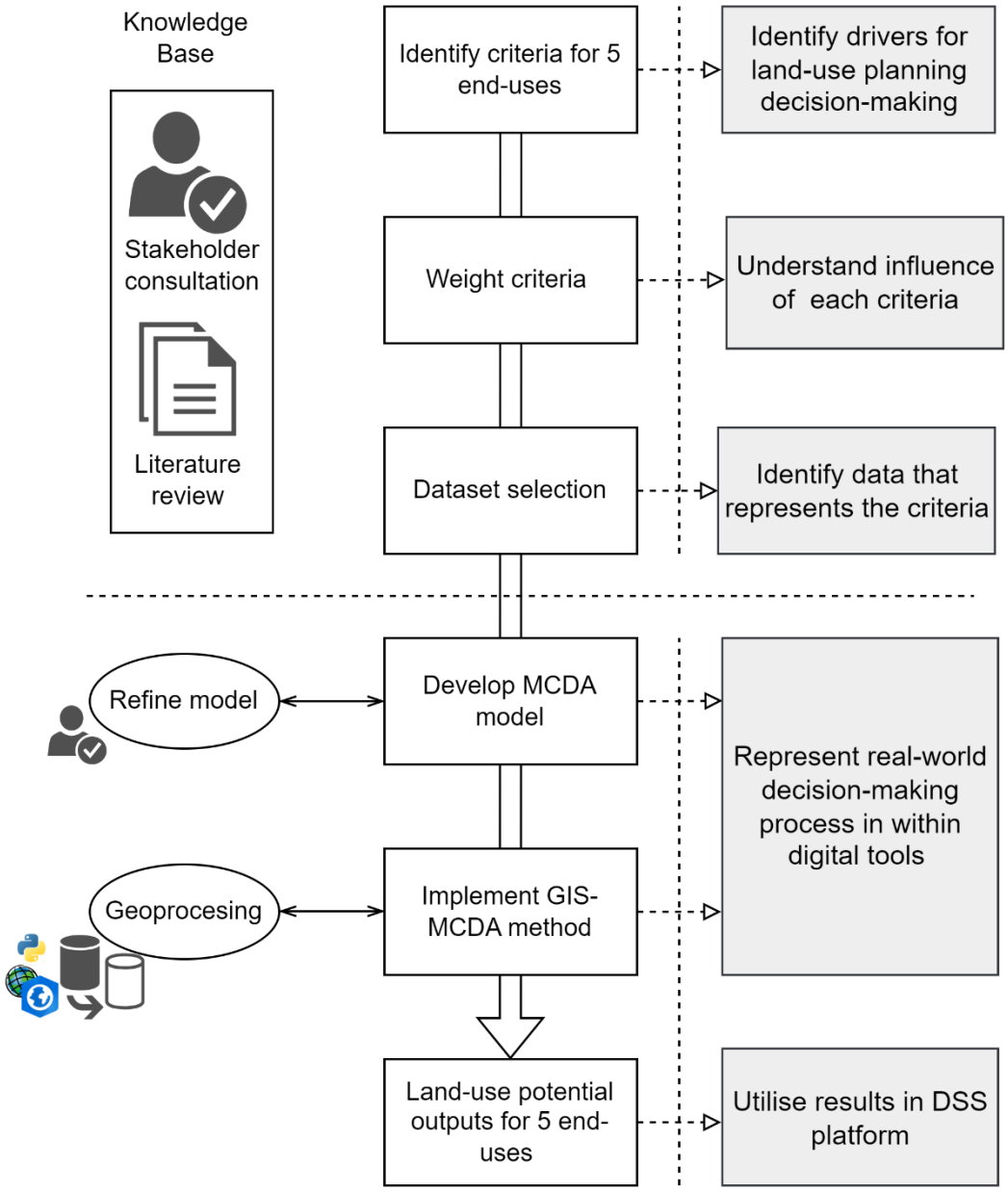


Figure 4.3 Overview of methodology approach for Land Use Potential outputs.

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 of strategic logistic hubs were digitised to calculate *distance to market.* For a full list of datasets used refer to Table 4.5 (Appendix 4.8).

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

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

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:

$$\text{Land Use Potential Score} = A_i^{Score} \div max(A_i^{Score})$$

All geoprocessing was performed using ArcGIS Pro and Python scripts to create Land Use Potential outputs. 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 allow them to be used in the suitability modelling workflow. Specifics of transformation applied to individual criteria-datasets can be found in Table 4.4 (Appendix 4.8).

The raster layers were created using a pre-generated empty raster (50 m x 50 m grid) dataset of the study area and were then reclassified, and aggregated by implementing the weighted sum model within the suitability modelling workflow within ArcGIS Pro.

Table 4.2 Land Use Potential criteria selected, including weightings.

Land use Type	**Criteria**	**Weighting (1 – 10)**	**Criteria Score**
Residential	Proximity to health infrastructure	7	400m - 1 0.66 - 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*	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) *	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 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
*Critical Criteria			

The final score for each cell was set to range from 0 to 1, and then categorised into user-friendly classes (Table 4.3). Selected source data attributes were preserved and presented in their respective final land use potential layers.

Table 4.3 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
0.01 – 0.19	Very Low Potential
0	Development Not Advised

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 was assigned to classes (Table 4.3). These land use potential maps were then clipped to the Post-Industrial Land area using the 'clip' function.

Next, 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 4.2) 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 land use potential layers were organised 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.

4.2.5 Module 2 - Ground risk

Ground risk data (Groundscreen) were shared with the authors 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 because of commercial constraints but is based on a GIS-MCDA methodology integrating a wide range of geological and environmental spatial data 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 Score 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 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 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 where they were 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.

4.2.6 Module 3 - Economic evidence

4.2.6.1 Remediation costs

Within the Groundscreen data product, there are specific fields that are to be used for calculating the estimated contamination and geotechnical remediation cost. Within the Groundscreen data product, contamination and geotechnical remediation costs were included per hexagon grid cell (0.25ha per cell). Groundscreen data were again converted to ESRI File Geodatabase format using conversions tools in QGIS to allow for straightforward geoprocessing.

Using ArcGIS Pro's Clip function, the dataset was clipped to the 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 published methodology for estimating remediation costs (Homes & Communities Agency, 2015). The cost estimation values were then joined to the study sites using the spatial join function, and two site summary cost datasets were produced for contamination and ground instability.

4.2.6.2 Estimated new build property sale price and land value

The estimated new build property sale price data theme consists of six datasets created for this project (Appendix 4.8.1). 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 Liverpool City Region Combined Authority's constituent LPAs and processed using Excel. A fuzzy-merge method was used to match the Price Paid and EPC data, because of inconsistencies in spelling, formatting, and input errors. The fuzzy-lookup add-in for Excel was used to match similar rows based on address. This matching process was performed multiple times to ensure accuracy. This process was implemented separately for houses and flats.

The full methodology for Estimated Property Sale price data and Land Value Estimates outputs are available in the Appendix (4.8.1). The economic evidence layers were configured and uploaded to ArcGIS Online as described for the other modules (Sections 4.2.4 and 4.2.5)

4.2.7 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.

The ESRI ArcGIS Experience Builder (EB) platform was selected for several reasons. The EB platform allows for the creation of web-mapping tools and has a large range of customisable widgets and functionality that could be implemented easily and placed within a desired interface configuration, then subsequently reconfigured as desired equally easily. Additionally, the use of EB fits within existing GIS workflows, used as part of the development of the research and underlying models. Other technical implementation options for the DSS prototype development considered included Leaflet (Leaflet, 2023), Carto (CARTO, 2023), Mapbox (Mapbox Inc., 2023) and the development of a fully bespoke web mapping application. These alternative options were deemed not to have sufficient immediate functionality needed for DSS prototyping, were too complex, or the time taken to gain the knowledge needed to use them was not proportionate for the level of prototyping required. Overall, Experience Builder was considered ideal for this stage of prototyping, allowing for all components and designs of DSS to be created and reconfigured efficiently and easily for user testing and iterative development purposes.

4.2.8 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 (Table 4.6, Appendix 4.8). 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 its ability to support decision making. Based on the feedback, improvements were implemented on the DSS, and future development needs and improvements were recorded (Table 4.7, Appendix 4.8).

4.3 Results

4.3.1 Decision Support System

The user journey through the DSS (Figure 4.4) was intentionally designed to provide stakeholders with a quick overview of sites before delving into the details of each module. The user journey was created with input from the project team and case-study stakeholders during the wireframing and early prototyping stages and was further refined based on feedback from user testing (Section 4.2.8). The general layout and functionality of the DSS interface are consistent across the three modules (Figure 4.5). The module

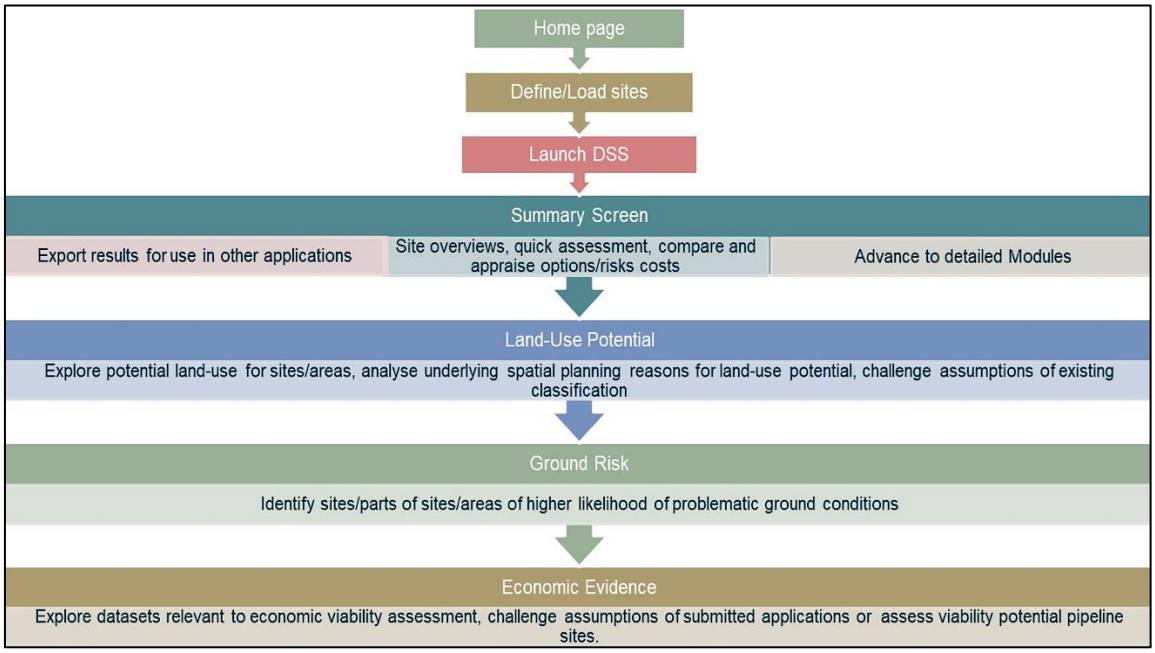


Figure 4.4 The user journey through the DSS.

navigation bar allows users to move between the three modules, preserving the previous. 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.

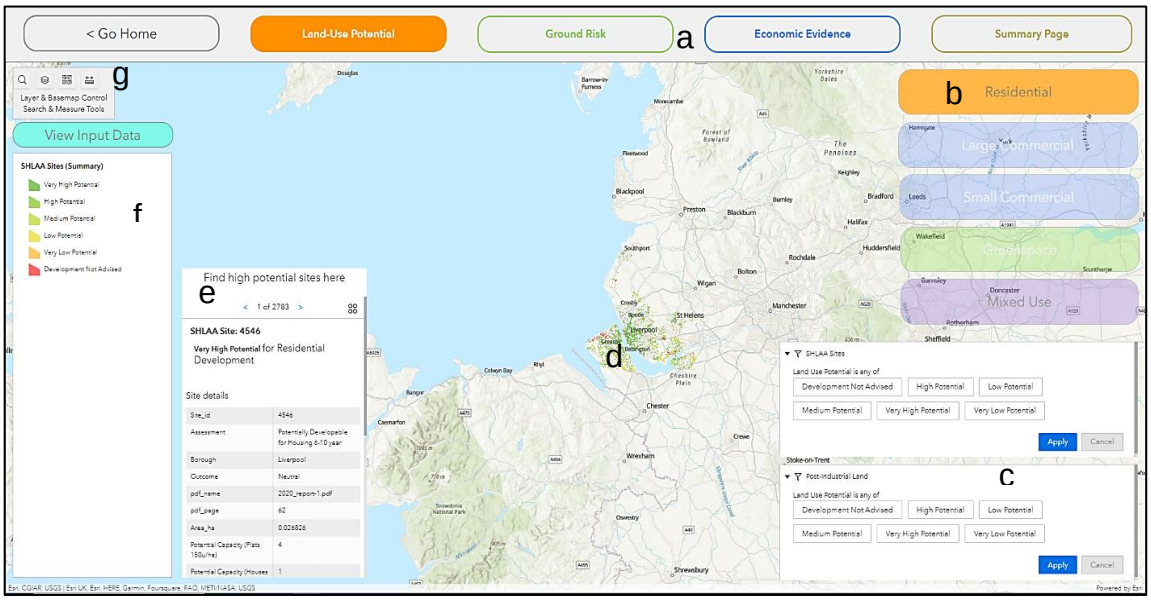


Figure 4.5 The user interface of the DSS, showing elements of general functionality are highlighted: Module navigation bar (a); In-Module navigation (b); Filtering tools (c); Map window (d); Summary tool (e); Legend (f); Layer control, basemap toggle, search, and measuring tools (g). Basemap attribution: Esri, Esri UK, CGIAR, USGS, HERE, Garmin, Foursquare, FAO, METI/NASA.

The principal data visualisation in the DSS takes place within the map window, where users can use their mouse or touchscreen to zoom, pan, and interact with the spatial data. 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 the visibility of spatial data layers (Post-Industrial Land, Site Summary, Site Detailed), as required. A basemap toggle allows users to change the underlying map shown in the map window (i.e., satellite view

vs topographic mapping), and the search tool allows the user to find any location of interest using the ArcGIS World Geocoding Service.

4.3.1.1 Reviewing high-level deliverability of sites

Whilst each module of the DSS allows users (i.e., Strategic Land user Planner, Brownfield Regeneration Officer) to investigate a different dimension of brownfield land use planning and development, when combined the DSS, and datasets presented within it and functionality, allow for rapid, high-level assessment of 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, the summary screen (Figure 4.6) allows users to select a site, or range of sites and returns the key classifications, scores, and values from the three modules. Additional functionality within the summary screen page includes a 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 (Figure 4.6).

Using the summary screen, the planning officer (i.e., Strategic Land user Planner, Brownfield Regeneration 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, addressing all of the user stories outlined in Table 4.1.

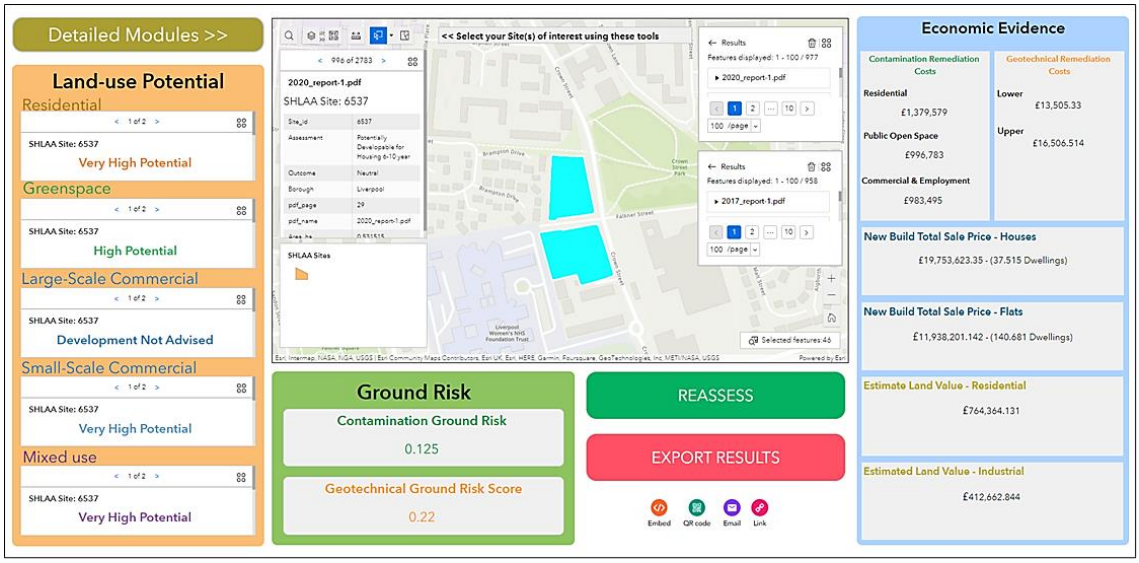


Figure 4.6 The user interface of the DSS for the summary screen. Basemap attribution: *Esri, Intermap, NASA, NGA, USGS, Esri Community Map Contributors, Esri UK, HERE, Garmin, Foursquare, GeoTechnologies Inc, METI/NASA.*

4.3.1.2 Assessing a site or areas 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 (i.e., Strategic Land user Planner, Brownfield Regeneration Officer, Digital Spatial Planning Officer) 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 (Figure 4.8) and Site Summary (Figure 4.7a) LUP layers, assist with carrying out high-level identification/comparison of many sites/areas for certain types of land use.

The site detailed layer (Figure 4.7b) allows for an intra-site assessment of land use potential on a 50 m x 50 m resolution. This allows users to identify areas of sites, particularly large sites, where different types of land use may be more suitable, helping to inform site layout, supporting the *Land Use Potential* user story (Table 4.1). The site detailed layer is supported by filtering tools, assisting the user with identifying sites of

areas of large sites that match their search criteria and helping to include/exclude sites/areas from their assessments.

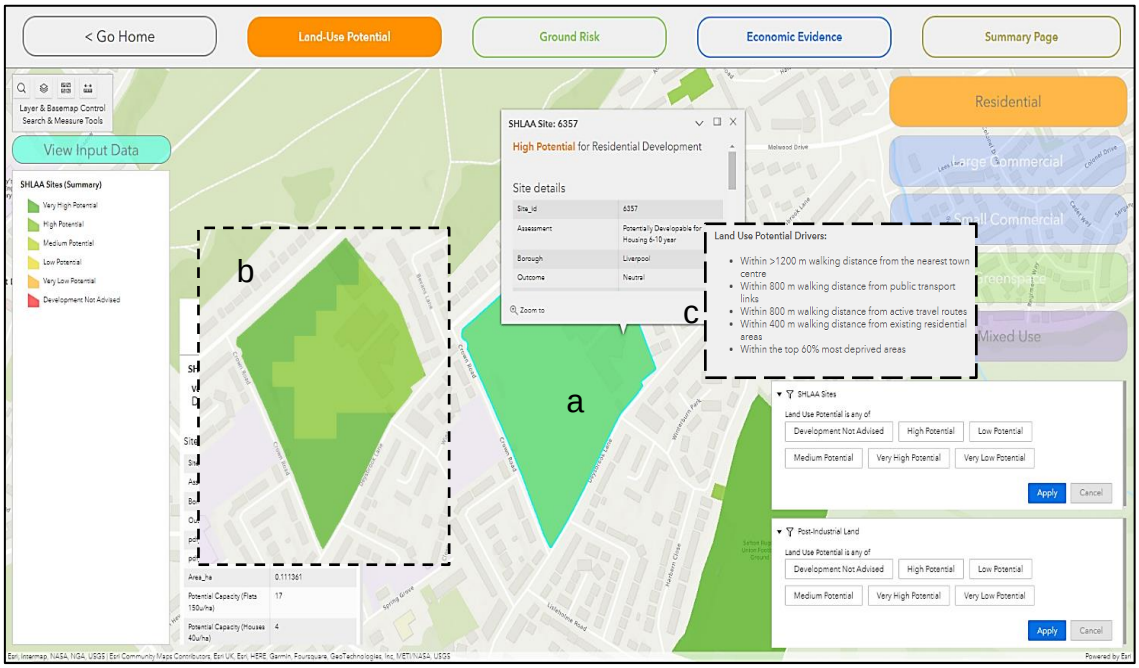


Figure 4.7 The user interface of the DSS for Land Use Potential Module showing site summary view (a), Site detailed view (b), and Land Use Potential drivers within the pop-up window (c). Basemap attribution: *Esri, Intermap, NASA, NGA, USGS, Esri Community Map Contributors, Esri UK, HERE, Garmin, Foursquare, GeoTechnologies Inc, METI/NASA.*

Users can 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 the 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 Figure 4.7c, pop-ups are configured in a way that presented users with 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 Figure 4.8, a 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, supporting the *Land Use Potential* user story (Table 4.1).

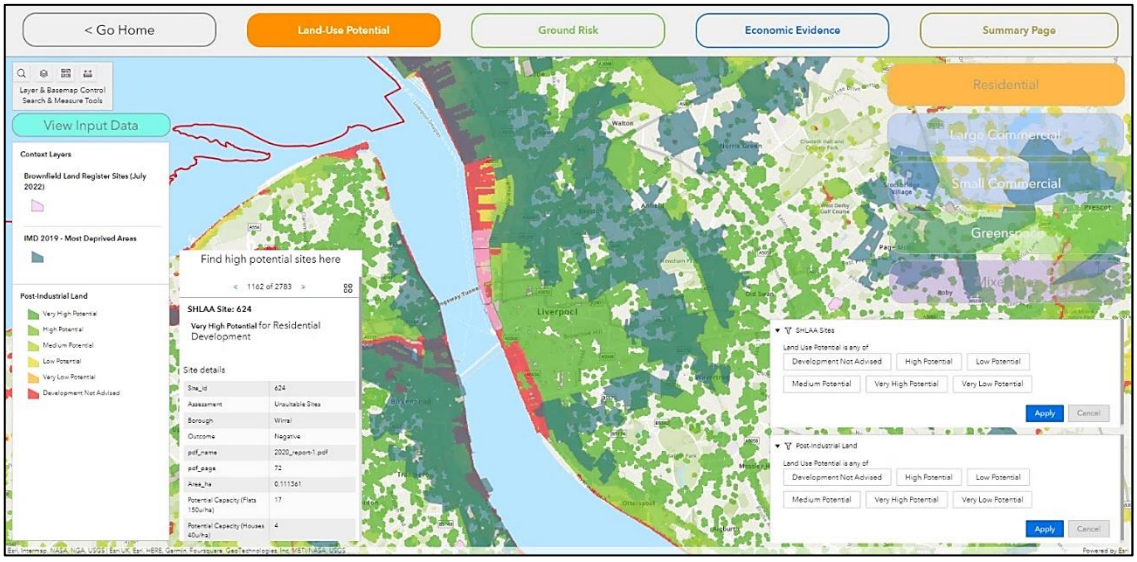


Figure 4.8 The user interface of the DSS for Land Use Potential Module showing Post-industrial land use Potential layer, overlain by contextual layers. Basemap attribution: *Esri, Intermap, NASA, NGA, USGS, Esri Community Map Contributors, Esri UK, HERE, Garmin, Foursquare, GeoTechnologies Inc, METI/NASA.*

4.3.1.3 Investigating ground risk of a site

The ground risk module allows users (i.e., Strategic Land user Planner, Brownfield Regeneration Officer) to interpret and understand the potential ground risk posed to a site/area by contamination and geotechnical hazards (Figure 4.9). Post-industrial land and site summary allow for high-level assessment, whereas site detailed view allows for intra-site identification of areas of higher risk. The site detailed view (Figure 4.9) aids 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, supporting the challenges outlined in the *Ground Conditions* user story (Table 4.1). If a user seeks to investigate the underlying reasons for a ground risk score, they can open the supporting data window (Figure 4.10), where they can load all of the input data and analyse it through detailed pop-ups. For example, Figure 4.10 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.

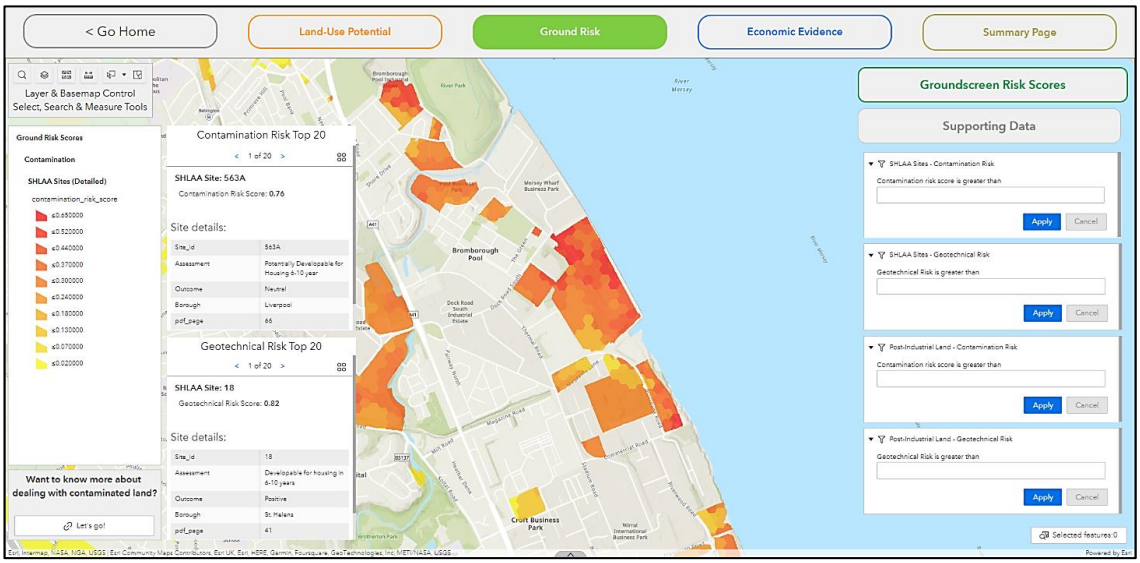


Figure 4.9 The user interface of the DSS for Ground Risk Module showing site detailed view for contamination risk, the linking button to supporting data window is also visible. Basemap attribution: *Esri, Intermap, NASA, NGA, USGS, Esri Community Map Contributors, Esri UK, HERE, Garmin, Foursquare, GeoTechnologies Inc, METI/NASA.*

In-map summary tools (Figure 4.9) within the ground risk module have been configured to show the highest-risk sites. This supports land use planners, and other stakeholders in the identification of sites within a portfolio where the most special intervention/funding/investigation may be needed to address abnormal ground conditions, assisting with understanding economic viability (Table 4.1). Also present in the ground risk module is a link to guidance on dealing with contaminated land (Figure 4.9).

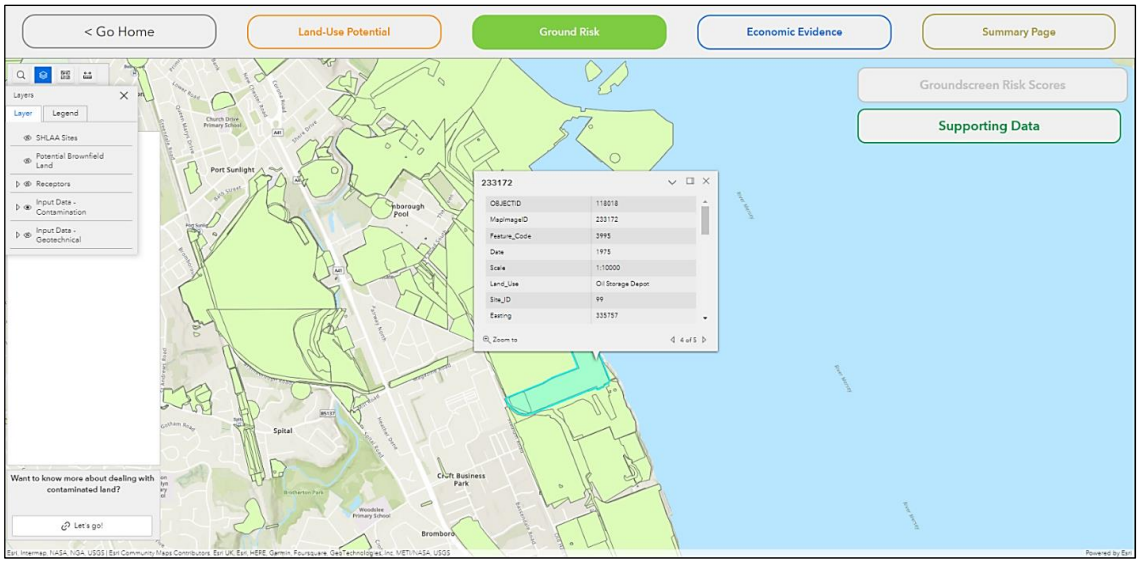


Figure 4.10 The user interface of the DSS for Ground Risk Module showing supporting data (in this case Historic Land use). Basemap attribution: *Esri, Intermap, NASA, NGA, USGS, Esri Community Map Contributors, Esri UK, HERE, Garmin, Foursquare, GeoTechnologies Inc, METI/NASA.*

4.3.2 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 (Table 4.6, Appendix 4.8) indicated positive attitudes toward 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 4.11 illustrates the DSS usability results. 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. Because of this, comments on this aspect were analysed further. This showed that users attributed this to technical difficulties experienced 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. When a strong, stable internet connection the DSS run smoothly and loads content quickly.

Key points established following the user feedback include:

- The land use potential module is deemed by most users to be accurate to their understanding of the site's potential. Most users commented how this is most useful when combined with their knowledge of a site area, feeding into their assessments.
- The ground risk module was also deemed to be accurate to users' experience and understanding of sites they were familiar with. Most users commented that it was a "good module to gain a 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 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 applications 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 was 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

Figure 4.11 Radar plots showing responses from stakeholders when asked to rank usability aspects of the DSS, scores are aggregated and averaged by stakeholder type.

testing workshop, to explore scenarios and discuss particulars of sites. This demonstrates how the 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 Table 4.6 (Appendix 4.8).

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 as they were either 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 Appendix 4.8.2.

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 Table 4.7 (Appendix 4.8). The methodology and details described in Section 4.2 are those used to create the most current version of the DSS.

4.4 Discussion

The DSS presented in this paper comprises both model-based and information-based approaches (Figure 4.12). 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.

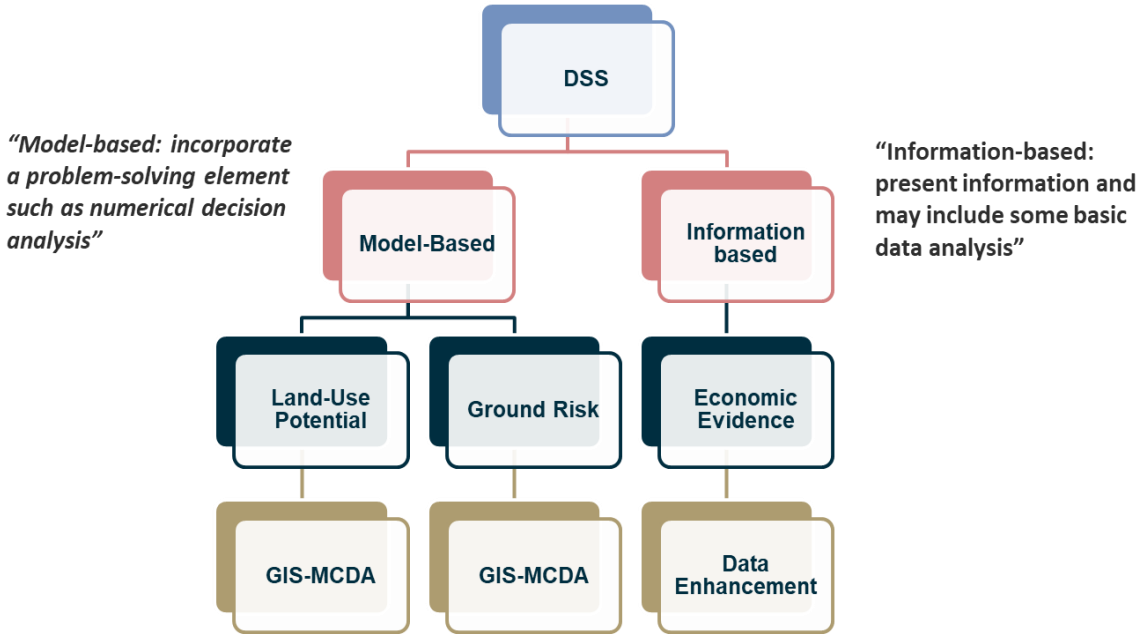


Figure 4.12 DSS Approach.

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 4.2.1). 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, giving the DSS the ability to support stakeholders in whichever way they need the information in to support a variety of decision making activities. The DSS may 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). The summary report can prove useful for the communication of findings and the provision of evidence to non-expert audiences. The ability to export data to a spreadsheet report and/or spatial data export may be utilised to support internal analysis and the discovery of new understanding/scenarios and interoperability between the DSS and other software systems.

The DSS presented here differs from many other such systems 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 DSSs research can be siloed in their 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., 2023a) and through the development of a detailed use case (Section 4.2.1). 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 the 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. 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., 2023a) (Chapter 3); 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 application. 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, as evidenced by finding from user testing.

Findings from user testing indicate that the decision support system presented here has a high degree of usability and is suitable for supporting stakeholders 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 stakeholders 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 is that a DSS, like the one presented, with a modular structure may become a 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 flexibility in meeting shifting areas of concern for the 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 presented in this research.

4.5 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 a 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 that intended users of the DSS understand the underlying methods, preventing the DSS from becoming a 'black box', where the inner workings of the system are not known or well understood. This allows stakeholders to accurately interpret DSS outputs for decision making as appropriate. Evaluation of the DSS was undertaken by means of extended user testing with a variety of public-sector stakeholders 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 planning decision tasks. The approach presented should serve to illustrate the creation of modern, user-led, brownfield DSSs. The next steps are to demonstrate the DSS with a case-study application and to verify and test the accuracy of land use potential models against real-world decision making. Once this is completed, implications to public-sector decision making and policy can be discussed.

4.6 Author contributions

E. Hammond: Conceptualization, Methodology, Analysis, Investigation, Writing-Original Draft, Visualization, 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.

4.7 References

Agostini, P., Pizzol, L., Critto, A., D'Alessandro, M., Zabeo, A., Marcomini, A., 2012. Regional risk assessment for contaminated sites Part 3: Spatial decision support system. Environ. Int. 48, 121–132. https://doi.org/10.1016/j.envint.2012.07.005

Ameller, J., Rinaudo, J.D., Merly, C., 2020. The Contribution of Economic Science to Brownfield Redevelopment: A Review. Integr. Environ. Assess. Manag. 16, 184–196. https://doi.org/10.1002/ieam.4233

Bartke, S., Schwarze, R., 2015. No perfect tools: Trade-offs of sustainability principles and user requirements in designing support tools for land-use decisions between greenfields and brownfields. J. Environ. Manage. 153, 11–24. https://doi.org/10.1016/j.jenvman.2015.01.040

Bennett, R., Bugri, J., Adade, D., Timo De Vries, W., 2023. Digital Twin for Active Stakeholder Participation in Land-Use Planning. L. 2023, Vol. 12, Page 538 12, 538. https://doi.org/10.3390/LAND12030538

Beriro, D., Nathanail, J., Salazar, J., Kingdon, A., Marchant, A., Richardson, S., Gillet, A., Rautenberg, S., Hammond, E., Beardmore, J., Moore, T., Angus, P., Waldron, J., Rodrigues, L., Nathanail, P., 2022. A decision support system to assess the feasibility of onshore renewable energy infrastructure. Renew. Sustain. Energy Rev. 168, 112771. https://doi.org/10.1016/J.RSER.2022.112771

Black, P., Stockton, T., 2009. Basic Steps for the Development of Decision Support Systems, in: Marcomini, A., Suter II, G.W., Critto, A. (Eds.), Decision Support Systems for Risk-Based Management of Contaminated Sites. Springer US, Boston, MA, pp. 1–27. https://doi.org/10.1007/978-0-387-09722-0_1

CABERNET, 2006. Sustainable Brownfield regeneration: CABERNET network report. University of Nottingham Land quality management report.

Cappai, F., Forgues, D., Glaus, M., 2019. A Methodological Approach for Evaluating

Brownfield Redevelopment Projects. Urban Sci. 2019, Vol. 3, Page 45 3, 45. https://doi.org/10.3390/URBANSCI3020045

Carlon, C., Pizzol, L., Critto, A., Marcomini, A., 2008. A spatial risk assessment methodology to support the remediation of contaminated land. Environ. Int. 34, 397-411. https://doi.org/10.1016/j.envint.2007.09.009

CPRE, 2022. State of brownfield report 2022 - [WWW Document]. URL https://www.cpre.org.uk/resources/state-of-brownfield-report-2022/ (accessed 4.26.23).

Critto, A., Agostini, P., 2009. Using multiple indices to evaluate scenarios for the remediation of contaminated land: The Porto Marghera (Venice, Italy) contaminated site. Environ. Sci. Pollut. Res. 16, 649–662. https://doi.org/10.1007/s11356-009-0194-5

Department for Levelling Up Housing and Communities, 2021. National design guide [WWW Document]. URL https://www.gov.uk/government/publications/national-design-guide (accessed 1.5.23).

ESRI, 2023. ArcGIS Experience Builder [WWW Document]. URL https://www.esri.com/en-us/arcgis/products/arcgis-experience-builder/overview (accessed 1.6.23).

European Union, 2010. Report on the workshop on Re-using Brownfield Sites and Buildings.

Fishburn, P.C., 1967. Letter to the Editor—Additive Utilities with Incomplete Product Sets: Application to Priorities and Assignments. Oper. Res. 15, 537–542. https://doi.org/10.1287/OPRE.15.3.537

Green, T.L., 2018. Evaluating predictors for brownfield redevelopment. Land use policy 73, 299–319. https://doi.org/10.1016/j.landusepol.2018.01.008

Groundsure, 2023. Groundscreen [WWW Document]. URL https://www.groundsure.com/products/groundscreen/ (accessed 5.3.23).

Hammond, E.B., Coulon, F., Hallett, S.H., Thomas, R., Hardy, D., Kingdon, A., Beriro, D.J., 2021. A critical review of decision support systems for brownfield redevelopment. Sci. Total Environ. 785, 147132. https://doi.org/10.1016/j.scitotenv.2021.147132

Hammond, E.B., Coulon, F., Hallett, S.H., Thomas, R., Hardy, D., Beriro, D.J., 2023a. Digital tools for brownfield redevelopment: Stakeholder perspectives and opportunities. J. Environ. Manage. 325, 116393. https://doi.org/10.1016/J.JENVMAN.2022.116393

Hammond, E.B., Coulon, F., Hallett, S.H., Thomas, R., Dick, A., Hardy, D., Dickens, M., Washbourn, E., Beriro, D.J., 2023b. From data to decisions: Empowering brownfield redevelopment with a novel decision support system. J. Environ. Manage. 347, 119145. https://doi.org/10.1016/J.JENVMAN.2023.119145

Homes & Communities Agency, 2015. Guidance on dereliction, demolition and remediation costs [WWW Document]. URL https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/414378/HCA_Remediation_Cost_Guidance_2015.pdf (accessed 11.1.19).

Homes England, 2018. Homes England Strategic Plan 2018--2023.

Huysegoms, L., Cappuyns, V., 2017. Critical review of decision support tools for sustainability assessment of site remediation options. J. Environ. Manage. 196, 278-296. https://doi.org/10.1016/j.jenvman.2017.03.002

Limasset, E., Bartke, S., Merly, C., Doisy, S., Dubromel, A., Pizzol, L., Martinát, S., Klusáček, P., Clozel, B., 2017. Prioritisation strategies for regional brownfield redevelopment: Perspectives & Feedback on existing tools and approaches. AquaConsoil Lyon 2017

Local Government Association, 2023. One Public Estate: Brownfield Land Release Fund (BLRF2) Round 2 [WWW Document]. URL https://www.local.gov.uk/our-support/one-public-estate/one-public-estate-brownfield-land-release-fund-blrf2-round-2-january (accessed 3.21.23).

Loures, L., Vaz, E., 2018. Exploring expert perception towards brownfield redevelopment benefits according to their typology. Habitat Int. 72, 66–76. https://doi.org/10.1016/j.habitatint.2016.11.003

Marcomini, A., Suter, G.W., Critto, A., 2009. Decision support systems for risk-based management of contaminated sites, Decision Support Systems for Risk-Based Management of Contaminated Sites. Springer US. https://doi.org/10.1007/978-0-387-

09722-0

Ministry of Housing Communities and Local Government, 2021. National Planning Policy Framework.

Office of Government Property, Local Government Association, Ministry of Housing Communities and Local Government, 2021. One Public Estate: Brownfield Land Release Fund April 2021 | Local Government Association [WWW Document]. URL https://www.local.gov.uk/ope-brownfield-land-release-fund (accessed 1.31.22).

Pettit, C., Bakelmun, A., Lieske, S.N., Glackin, S., Hargroves, K. 'Charlie,' Thomson, G., Shearer, H., Dia, H., Newman, P., 2018. Planning support systems for smart cities. City, Cult. Soc. 12, 13–24. https://doi.org/10.1016/J.CCS.2017.10.002

Pizzol, L., Critto, A., Agostini, P., Marcomini, A., 2011. Regional risk assessment for contaminated sites Part 2: Ranking of potentially contaminated sites. Environ. Int. 37, 1307–1320. https://doi.org/10.1016/j.envint.2011.05.010

Pizzol, L., Critto, A., Marcomini, A., 2009. A spatial decision support system for the risk-based management of contaminated sites: The DESYRE DSS, in: Decision Support Systems for Risk-Based Management of Contaminated Sites. Springer US, pp. 157–178. https://doi.org/10.1007/978-0-387-09722-0_8

Pizzol, L., Zabeo, A., Klusáček, P., Giubilato, E., Critto, A., Frantál, B., Martinát, S., Kunc, J., Osman, R., Bartke, S., 2016. Timbre Brownfield Prioritization Tool to support effective brownfield regeneration. J. Environ. Manage. 166, 178–192. https://doi.org/10.1016/j.jenvman.2015.09.030

Purucker, S.T., Stewart, R.N., Welsh, C.J.E., 2009. SADA: Ecological Risk Based Decision Support System for Selective Remediation, in: Marcomini, A., Suter II, G.W., Critto, A. (Eds.), Decision Support Systems for Risk-Based Management of Contaminated Sites. Springer US, Boston, MA, pp. 1–18. https://doi.org/10.1007/978-0-387-09722-0_11

Rosén, L., Back, P.E., Söderqvist, T., Norrman, J., Brinkhoff, P., Norberg, T., Volchko, Y., Norin, M., Bergknut, M., Döberl, G., 2015. SCORE: A novel multi-criteria decision analysis approach to assessing the sustainability of contaminated land remediation. Sci.

Total Environ. 511, 621-638. https://doi.org/10.1016/j.scitotenv.2014.12.058

Rosén, L., Norrman, J., Norberg, T., 2013. SCORE: Multi-Criteria Analysis (MCA) for Sustainability Appraisal of Remedial Alternatives2013. "SCORE: Multi-Criteria Analysis (MCA) for Susta, in: Second International Symposium on Bioremediation and Sustainable Environmental Technologies (Jacksonville, FL;). JAck.

Söderqvist, T., Brinkhoff, P., Norberg, T., Rosén, L., Back, P.E., Norrman, J., 2015. Cost-benefit analysis as a part of sustainability assessment ofremediation alternatives for contaminated land. J. Environ. Manage. 157, 267-278. https://doi.org/10.1016/j.jenvman.2015.04.024

Sorvari, J., Seppälä, J., 2010. A decision support tool to prioritize risk management options for contaminated sites. Sci. Total Environ. 408, 1786-1799. https://doi.org/10.1016/j.scitotenv.2009.12.026

Stezar, I.C., Pizzol, L., Critto, A., Ozunu, A., Marcomini, A., 2013. Comparison of risk-based decision-support systems for brownfield site rehabilitation: DESYRE and SADA applied to a Romanian case study. J. Environ. Manage. 131, 383-393. https://doi.org/10.1016/j.jenvman.2013.09.022

The Land Trust, 2015. Brownfield as green space - The Land Trust [WWW Document]. URL https://thelandtrust.org.uk/who-we-are/policy/brownfield-green-space/?doing_wp_cron=1573832200.2426180839538574218750 (accessed 11.15.19).

Three Dragons, 2023. Three Dragons | Independent Consultancy [WWW Document]. URL https://www.three-dragons.co.uk/ (accessed 2.14.23).

UNEP, 2020. UNEP Enviornmental and Social Sustainability Framework (ESSF).

Van Liedekerke, M., Prokop, G., Rabl-Berger, S., Kibblewhite, M., Louwagie, G., 2014. Progress in the Management of Contaminated Sites in Europe. https://doi.org/10.2788/4658

Zabeo, A., Pizzol, L., Agostini, P., Critto, A., Giove, S., Marcomini, A., 2011. Regional risk assessment for contaminated sites Part 1: Vulnerability assessment by multicriteria decision analysis. Environ. Int. 37 (8), 1295-1306. https://doi.org/10.1016/j.envint.2011.05.005

4.8 Appendix

Table 4.4 Land Use Potential MCDA models.

Land-Use Type	Criteria	Weighting Relative Importance As determined by case study stakeholders (1-10)	Justification for Criteria	Evidence base	Distance Zones / Classes	MCDA Attribute Score	Rationale for	Max Criteria Score
Residential	Proximity to Health Infrastructure	7	Proximity to health care providers can make GP consultants easier to get to, good for local community building Being close to hospitals is good for when emergencies happen, also good for employment in local community	National Design Guide - 'Movement' Case Study Stakeholder Engagement - 15-minute neighbourhood concept.	400m 800m 1200m	400m - 1 800m - 0.66 1200m - 0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	7
	Proximity to active travel routes	9	Making sure people have access to footpaths and cycle paths around their homes	National Design Guide - 'Movement' https://www.transportfornewhomes.org.uk/wp-content/uploads/2018/07/transport-for-new-homes-summary-web.pdf Case Study Stakeholder Engagement	400m 800m 1200m	400m - 1 800m - 0.66 1200m - 0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	9

	Proximity to public transport	9	People close to public transport links to help them get to work, social etc good for reducing carbon footprint etc		400m 800m 1200m	400m - 1 800m - 0.66 1200m -0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	9
	Proximity to roads	8	Road travel is still essential		1600m >1600m	1600m - 1 >1600m - 0.5	Areas within 1 mile of major road links are likely to be more successful as residential developments than those not. Evidenced from Case Study Stakeholder Engagement	8
	Proximity to town centres	8	Part of building sense of community - 20-minute neighbourhood concept	Case Study Stakeholder Engagement	400m 800m 1200m	400m - 1 800m - 0.66 1200m -0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	8
	Proximity to Existing Shops (Food)	8	Proximity to supermarkets and shops important in community building	National Planning Policy Framework - Ch 8 National Design Guide - 'Context' Case Study Stakeholder Engagement	400m 800m 1200m	400m - 1 800m - 0.66 1200m -0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	8

	Proximity to Community Venues	7	Important in the creation of local communities.	Case Study Stakeholder Engagement	Class 1 (5 Mins) - 1 Class 2 (10 Mins) - 0.66 Class 3 (15 Mins) - 0.33	Class 1 (5 Mins) - 1 Class 2 (10 Mins) - 0.66 Class 3 (15 Mins) - 0.33	The dataset used to represent this criterion has already zoned Case Study region by its walking distance to community venues and assigned a score. These scored walkability zones are then divided into five natural break classes and then scoring the highest scored areas a full weight of 1, down to 0.2 for the worst performing area. Five classes give a good level of detail for the city region based on distribution of scores in the source dataset.	7
	Proximity to Green spaces	8	Local community building, space for children to play etc. Number of well understood benefits to living near green space.	National Design Guide - 'Nature' Case Study Stakeholder Engagement https://www.ons.gov.uk/economy/environmentalaccounts/articles/urbangreenspacesraisenearbyhousepricesbyanaverageof2500/2019-10-14	400m 800m 1200m	400m - 1 800m - 0.66 1200m -0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	8
	Proximity to Education establishments	9	Important in the creation of local communities.	Case Study Stakeholder Engagement	400m 800m 1200m	400m - 1 800m - 0.66 1200m -0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	9

	Proximity to Cultural sites	6	Important in the creation of local communities.	Case Study Stakeholder Engagement	400m 800m 1200m	400m - 1 800m - 0.66 1200m -0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	6
	Within Greenbelt area (Critical Criteria)	N/A	Residential Development not permitted in Greenbelt areas	Case Study Stakeholder Engagement National Planning Policy Framework	N/A	N/A	N/A	N/A
	Population Density	7	Areas of high population density need more housing available.	Case Study Stakeholder Engagement National Planning Policy Framework - Para. 121	N/A	Class 10 - 1 Class 9 - 0.9 … Class 2 - 0.2 Class 1 - 0.1	By dividing this data into 10 classes based on natural breaks (Jenks), with the areas of high value being assigned the full weighting score 1, and so on down the 10 classes, 10 classes give suitable granularity to assess the whole city region area.	7
	Flood Risk zone 1 & 2	7	Riskier to build on a flood plain, control measures need to be put in place, less preferable	Government guidance: https://www.gov.uk/guidance/flood-risk-and-coastal-change#areas-at-risk-of-flooding Case Study Stakeholder Engagement	N/A	Zone 1 – 1 Zone 2 – 0.5	Areas in food risk zone 1 are more preferable to flood risk 2 areas for development, so the given maximum score of 1, whereas areas on floor risk zone 2 are given 0.5 to represent the less preferable choice.	7

	Flood Risk Zone 3	N/A	Residential Development not permitted in Flood Risk Zone 3	National Planning Policy Framework Case Study Stakeholder Engagement	N/A	N/A	N/A	N/A
	Proximity to sites of natural value	7	Want to preserve existing sites of ecological value	Case Study Stakeholder Engagement	N/A	N - 1 Y - 0.5	Sites that don't intersect with Existing natural value are more preferable for development, so the given maximum score of 1, whereas sites that do are given 0.5 to represent the less preferable choice.	7
Large-Scale Commercial	Access to Motorway	9	Good for commercial employment builds to be close to road links to allow works and customers good access to the site	Case Study Stakeholder Engagement National Design Guide - 'Movement'	1600 2500m 3000m	1600m - 1 2500m - 0.66 3200m - 0.33	It is preferable for large-commercial sites to be 1.5 miles (approx. 2500m) from motorway road junction, there for weighting score of 1, anything beyond ~ 2 miles is not preferable, so up to 3500 m is given preference score of 0.33. Evidence - Case Study Criteria Workshop	9
	Distance from residential areas	7	Large-scale commercial can impact residential developments with noise, light pollution, and other pollution/disturbance/ blight.	Stakeholder Engagement -	250m 500m 750m 1000m 1250m 1500m	250m - 0.2 500m - 0.4 750m - 0.6 1000m - 0.8 1250m - 1 1500m	Further away from residential is preferable, 2km is deemed to be far enough to not cause any disturbance, classes of lower preference are every 500m. Evidenced from Case Study Stakeholder Engagement	7
	Size of site	N/A	Minimum 4ha for large-scale commercial to allow for building footprint and hard landscaping (car parks, lorry yards etc)	Case Study Stakeholder Engagement	N/A	N/A	N/A	**N/A**

	Distance to Market	8	Access to goods-out/good-in ports/terminals required for large-scale commercial	Case Study Stakeholder Engagement	2500m 5000m 7500m	2500m - 1 5000m - 0.66 7500m - 0.33	It is preferable for large-commercial sites to be 1.5 miles from dist. to market features so there for weighting score of 1, anything beyond ~ 5 miles is not preferable, so up to 7500m is given preference score of 0.33. Evidenced from Case Study Stakeholder Engagement	8
	Rail access	8	Rail access, similar to multi-modal access, however this criterion assess proximity to rail lines - new terminal, railway line offshoot could be set up	Case Study Stakeholder Engagement	2500m 3000m 3500m	2500m - 1 3000m - 0.66 3500m - 0.33	It is preferable for large-commercial sites to be 1.5 miles (approx. 2500m) from railway lines, there for weighting score of 1, anything beyond ~ 2 miles is not preferable, so up to 3500 m is given preference score of 0.33. Evidenced from Case Study Stakeholder Engagement	8
	Public transport	8	People generally want to be close to public transport links to help them get to work, social etc good for reducing carbon footprint etc	National Design Guide - 'Movement'	400m 800m 1200m	400m - 1 800m - 0.66 1200m -0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	8
	Active Travel	8	Active travel route for workers to get to work, promoting sustainable transport	Case Study Stakeholder Engagement National Design Guide - 'Movement'	400m 800m 1200m	400m - 1 800m - 0.66 1200m -0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	8

	Road Travel	9	Road travel still big priority for large-scale commercial	Case Study Stakeholder Engagement	200m 300m 400m 500m	200m - 1 300m - 0.75 400m - 0.50 500m - 0.25	Closer to road links the better - link roads can be built. Beyond 500m is unpreferable, so four classes every 100m from 500 to 200m. Evidenced from Case Study Stakeholder Engagement	9
Small-Scale Commercial	Public transport	10	People generally want to be close to public transport links to help them get to work, social etc good for reducing carbon footprint etc	Case Study Stakeholder Engagement National Design Guide - 'Movement'	400m 800m 1200m	400m - 1 800m - 0.66 1200m -0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	10
	Active Travel	9	Active travel route for workers to get to work, and shoppers to get to the shops, promoting sustainable transport	Case Study Stakeholder Engagement National Design Guide - 'Movement'	400m 800m 1200m	400m - 1 800m - 0.66 1200m -0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	9

	Proximity to Town centres	8	Part of building sense of community - 20-minute neighbourhood concept	Stakeholder Engagement	400m 800m 1200m	400m - 1 800m - 0.66 1200m -0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	8
	Proximity to residential development	8	Part of building sense of community - 20-minute neighbourhood concept	Case Study Spatial Development Strategy Stakeholder Engagement	400m 800m 1200m	400m - 1 800m - 0.66 1200m -0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	8
	IMD 2019	8	Areas of deprivation may see improvement in economic and social indicators with the development of new small-scale commercial developments	Case Study Stakeholder Engagement	N/A	Class 10 - 1 Class 9 - 0.9 … Class 2 - 0.2 Class 1 - 0.1	By dividing this data into 10 classes based on natural breaks (Jenks), with the areas of high value being assigned the full weighting score 1, and so on down the 10 classes, 10 classes give suitable granularity to assess the whole city region area. Evidenced from Case Study Stakeholder Engagement	8
Greenspace	Proximity to another greenspace	8	In order to create functional greenspace and green corridors, greenspaces can be chained together	Case Study Stakeholder Engagement	100m 200m 300m 400m 500m	100m - 1 200m - 0.8 300m - 0.6 400m - 0.4 500m - 0.2	Greenspace within 100m of another greenspace highly preferable for 'chaining' this association of greenspaces gets less preferable beyond 500m just beyond 5 mins walk time. Evidenced from Case Study Stakeholder Engagement	8

	Proximity to schools	8	Green space close to schools to build community, also benefits for children's education and men' health also kids could use as recreation areas etc	National Design guide - ' Context' + 'Nature' Case Study Stakeholder Engagement https://www.unicef.org/media/102391/file/Necessity%20of%20Urban%20Green%20Space%20for%20Children%E2%80%99s%20Optimal%20Development.pdf	400m 800m 1200m	400m - 1 800m - 0.66 1200m -0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	8
	Proximity to residential	8	Functional greenspace around areas of residential development - helping to build local community and sustainable and green neighbourhoods	Case Study Stakeholder Engagement	400m 800m 1200m	400m - 1 800m - 0.66 1200m -0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	8
	Sustainable transport (active travel)	9	Active travel links important for public access to parks via suitable and green transport routes	Case Study Stakeholder Engagement National Design Guide - 'Movement'	400m 800m 1200m	400m - 1 800m - 0.66 1200m -0.33	Walkability Concept - 400m is 5 minutes walking (Highly preferable, therefore max score of 1), 800m is 10 minutes walking (next most preferable, therefore 2/3rds of max score - 0.66), 1200m is 15 minutes walking (next preferable,1/3rds of max score = 0.33). Outside of this is not preferable. When we divide the three walkability zones into equal zones of preference, we get 1, 0.66, 0.33. Evidenced from Case Study Stakeholder Engagement	9

	Flood Risk Zones	8	Areas of flood risk, may be difficult to develop as residential or commercial due to planning controls needs, meaning that these areas may be better developed as greenspace or BGI	Case Study Stakeholder Engagement	N/A	Zone 3 - 1 Zone 2 - 0.66 Zone 1 - 0.33	As other developments cannot be built in flood risk zone 3, potential greenspace sites in this area will be scored as 1 as it allows the site in FLR 3 to still potentially be used. Evidence - Case Study Stakeholder Engagement	8
	Noise buffer around roads 'Tranquillity zones'	8	Creation of green 'stand-off' zones around major roads	Case Study Stakeholder Engagement	1600m >1600m	1600m - 1 >1600m - 0.5	Existing Cranfield research on Tranquillity zones, suggests 1 mile (1600M)	8
	IMD 2019	8	Areas of high deprivation may be aided by the development of community greenspace	Case Study Stakeholder Engagement	N/A	Class 10 - 1 Class 9 - 0.9 … Class 2 - 0.2 Class 1 - 0.1	By dividing this data into 10 classes based on natural breaks (Jenks), with the areas of high value being assigned the full weighting score 1, and so on down the 10 classes, 10 classes give suitable granularity to assess the whole city region area. Evidenced from Case Study Stakeholder Engagement	8
	Public Health improvement areas	7	Areas of high deprivation (health indicators may be aided by the development of community greenspace, leading to a potential improvement in health indicators	Case Study Stakeholder Engagement	N/A	Class 10 - 1 Class 9 - 0.9 … Class 2 - 0.2 Class 1 - 0.1	By dividing this data into 10 classes based on natural breaks (Jenks), with the areas of high value being assigned the full weighting score 1, and so on down the 10 classes, 10 classes give suitable granularity to assess the whole city region area. Evidenced from Case Study Stakeholder Engagement	7
	Proximity to sites of natural value	3	Developing areas around protected sites as greenspace can help to create standoff zones and preserve natural value sites. Other development types might not be able to be developed close to these protected sites other than greenspace.	Case Study Stakeholder Engagement	100m	100m buff - 1 N - 0.5	Sites that intersect with Existing natural value are more preferable for greenspace development, so the given maximum score of 1, whereas sites that do not are given 0.5 to represent the less preferable choice. Evidenced from Case Study Stakeholder Engagement	3

Table 4.5 Land use potential source datasets.

Criteria	Dataset	Source	Link
Proximity to Health Infrastructure	GP Surgeries in England	Data.gov.uk	https://www.data.gov.uk/dataset/7eefedf4-0d8d-4ce6-9001-f85979e49ec9/location-of-general-practices-gps-surgeries
Proximity to Health Infrastructure	A & E Departments in England	data.world	https://data.world/robbin/nhs-ae-location-data
Proximity to Town centres	Retail Centre Boundaries	Consumer Data Research Centre (CDRC)	https://data.cdrc.ac.uk/dataset/retail-centre-boundaries-and-open-indicators
Proximity to Existing Shops	Geolytix Retail Points (Supermarkets)	Geolytix	https://geolytix.com/blog/supermarket-retail-points/
Proximity to Community Venues	Access to Healthy Assets & Hazards (Leisure)	Consumer Data Research Centre (CDRC)	https://data.cdrc.ac.uk/dataset/access-healthy-assets-hazards-ahah
Proximity to Green spaces	OS Open Greenspace	Ordnance Survey (OS)	https://www.ordnancesurvey.co.uk/business-government/products/open-map-greenspace
Proximity to Education establishments	Schools in England	Data.gov.uk	https://get-information-schools.service.gov.uk/Downloads
Proximity to Cultural sites	National Heritage List for England (NHLE)	Historic England	https://historicengland.org.uk/listing/the-list/data-downloads/
Areas of high Population Density	UK Gridded Population	Centre for Ecology and Hydrology (CEH)	https://catalogue.ceh.ac.uk/documents/0995e94d-6d42-40c1-8ed4-5090d82471e1
Flood Risk Zone 1 & 2	Flood Risk Zones	Environment Agency	https://www.data.gov.uk/dataset/7792054a-068d-471b-8969-f53a22b0c9b2/indicative-flood-risk-areas-shapefiles

Flood Risk Zone 3	Flood Risk Zones	Environment Agency	https://www.data.gov.uk/dataset/7792054a-068d-471b-8969-f53a22b0c9b2/indicative-flood-risk-areas-shapefiles
Proximity to sites of Natural Value	Special Protection Areas (SPA), National Nature Reserves (NNR), Local Nature Reserves (LNR), Designated Ancient Woodland, Biosphere Reserves, Forest Parks, Proposed Ramsar Sites, Possible, Special Areas of Conservation (pSAC), Potential Special Protection Areas (pSPA), Nitrate Sensitive Areas, Nitrate Vulnerable Zones, SSSI Impact Risk Zones, SSSI Units, Priority Habitat Inventory, Habitat Networks	Natural England	https://naturalengland-defra.opendata.arcgis.com/
Access to Motorway	OpenStreetMap (Motorways)	OpenStreetMap	https://www.openstreetmap.org/#map=6/54.915/-3.428
Distance to market	Liverpool Ports/Freight Terminals	Created for this research	N/A
Proximity to residential areas	OpenStreetMap Residential Area	OpenStreetMap	https://www.openstreetmap.org/#map=6/54.915/-3.428
Rail access	OpenStreetMap	OpenStreetMap	https://www.openstreetmap.org/#map=6/54.915/-3.430
Proximity to Public transport	NaPTAN	data.gov.uk	https://www.data.gov.uk/dataset/ff93ffc1-6656-47d8-9155-85ea0b8f2251/national-public-transport-access-nodes-naptan

Proximity to Active Travel routes	OpenStreetMap (Footpaths, Cycle paths, Roads)	OpenStreetMap	https://www.openstreetmap.org/#map=6/54.915/-3.428
Proximity to roads	OpenStreetMap	OpenStreetMap	https://www.openstreetmap.org/#map=6/54.915/-3.428
Indices of multiple deprivation 2019	IMD 2019	data.gov.uk	https://www.gov.uk/government/statistics/english-indices-of-deprivation-2019
Proximity to Greenbelt	English local authority Green Belt dataset	data.gov.uk	https://www.data.gov.uk/dataset/ccb505e0-67a8-4ace-b294-19a3cbff4861/english-local-authority-green-belt-dataset
Noise buffer around roads 'Tranquillity zones'	OpenStreetMap	OpenStreetMap	https://www.openstreetmap.org/#map=6/54.915/-3.428
Public Health improvement areas	IMD 2019 (Health)	data.gov.uk	https://www.gov.uk/government/statistics/english-indices-of-deprivation-2019

Table 4.6 User testing results.

Question/ Session Attendee		S1-1	S1-2	S2-3	S2-4	S2-1	S2-2	S2-3	S3-1	S3-2	S3-3	S3-4	S3-5	S3-6	S4-1	S4-2
Job Title		Principal Planning Officer	Senior Planner - Policy	Head of planning	Contaminated land specialist	Building Decarbonisation Advisor	Housing Graduate	Local Energy Lead (LCRCA)	Spatial Planning officer	Housing Delivery Manager	Data Analyst	Spatial Planning Officer	Investment Associate	Housing Graduate	Lead Officer - Spatial Planning	One Public Estate and Land Commission officer
Years experience		20	4 years	19	32	40	1	10	3	18	5	3	17	1	30	3
Experience with GIS		5	3	3	3	5	1	2	1	1	4	1	0	3	2	3
Aspect Scoring Table	**Ease of use**	4	4	4	4	5	3	5	5	4	5	5	4	3	5	5
	Comments: Ease of Use	Instructions would have been helpful for the user	N/A	N/A	Instructions would be really helpful	Intuitive and simple navigation		Straight forward and interactive			Would be useful to have a note explained what ground risk score means	Easy to get the hang off and play with. Nice to have options of summary/detailed	Easy to use and clear, just need more time to get used to the system		Seems to be very easy to use	Data very clear
	User Interface (Look and feel)	4	5	5	4	5	2	5	5	4	5	5	4	4	5	5
	Comments: User Interface	N/A	N/A	N/A	N/A	A very familiar layout through ArcGIS	Not so intuitive sometimes harder to find could do with some changes where popups appear	N/A			Very intuitive and can quickly compare sites visually	Nice and simple and mostly intuitive, would-be a pro after a day of practice	Clearly set out and easy to use	Summary page is very good plus easy to toggle for specific layers	N/A	Very Clear, colour coded, Summary page extremely helpful
	DSS Layout/Flow	4	4	4	4	4	2	4	5	3	4	5	3	3	5	5
	Comments: DSS Layout/Flow	Easy to move between the tabs but helpful if it takes you back to the same site/place and zoom	N/A	N/A	Appreciate it's still in development - would be good to stay in location between tabs, would make it easier to move between assessments modules	A little shuddery between pages (Internet connection mostly)	Quite stop start at times (internet connection), popups sometimes obstruct other things. Sometimes hard to find tables	Can be improved a bit when switching from a selection to another			Would be good to keep site selected throughout the DSS	Makes sense and helps tell a story of the site	Slow - may be office Wi-Fi		N/A	N/A

	Content **- Presentation of data** **- Relevance of data** **- Interaction with data**	5	4	4	4	5	5	5	5	5	4	5	4	4	5	5
	Comments: Content	Presentation really good	Levels of criteria are good. There is so much information that we currently have in excel sheet so nice to visual put it all together in an easy format	N/A	N/A	Very useful content, good navigation from topic to topic	very clear presentation of data, exceptionally relevant to role, and very able to combine elements	N/A			Good economic information from benchmarks.	Greenbelt, planning policy/status /history would be handy to filter	Good amount of information and detail	Layering of data is good good interaction/presentation good relevant of data for my work	N/A	Some data slightly outdated (SHLAA example sites), but would be easily updated in the full application
	Ease of extracting information from DSS	4	5	4	5	5	4	5	5	4	4	4	4	4	5	5
	Comments: Ease of extracting info from DSS	N/A	The summary tool is very good		N/A	Good, but the tables[pop-ups] could be longer in display length.	When fund, info was clear and very easy to see where the information had come from and where it matches up	N/A			Export information?	Glossary would be handy at times or what/why this info contains		Summary page is very useful after testing different output layers it was useful having all in for a site in one place	This would come with more use of the system, for a luddite like me it would take time initially	N/A

Accuracy of outputs: Land-Use Potential	Appears to be accurate for the sites I looked at	Yes - greenspace; layer was a bit off, but understand that this is an early-stage spatial assessment, and that local knowledge is needed for full assessment	Overall, very accurate accurate in identifying brownfield land (post-industrial land layer) of the sites I looked at I would agree the DSS is accurate for residential, small-commercial, and large commercial. Development not advised for areas in flood zone 3 accurate some areas of high contamination could influence the land use potential too!		There is an ideal summary of the criteria and various issues.	Definitely good with my knowledge of sites and the level of detail was great. Subarea of not advised' matched with the ubique topography and constraints of the site I am working on for both residential and commercial.	Very good outputs and a lot of supporting data to justify and each of the land-uses	Accurate for the sites I looked at. Allows for detailed analysis of sites providing useful information on its suitability	Accurate land-use outputs, and easy-to-use		High accuracy for the sites I compared and looked into	Really clear - fits well with existing knowledge of sites	Very accurate. One of the more useful and accurate outputs. Useful In terms of spatial planning most accurate of the three modules	I ran a few sites and the outputs compared with the real-life situation	Appears to be very accurate for all land use potential end-uses
Accuracy of outputs: Ground Risk Module	Not sure, not my area of expertise	Good for understanding and knowing what underlying risks are for sites, supporting data good to have too	Not my area of specialism	Broadscale looks reasonable	Really good as it shows lots of complex data, simplified.	Again, the risk scores matched my knowledge of the site, historical land use information for a section of the interlaps exactly with the high-risk areas, so good to see underlying drivers.	very accurate with a lot of historic data to back it up	This really helpful from a planner's point of view to identify sites in terms of viability. Would be helpful to filter by ranges of or provide a less than filter	Conscious that the remediation costs might be outdated perhaps HCA2015+ more recent industry data		Really detailed with a great depth of supporting data that would justify planning decision	Good and clear info again fits well with knowledge of the site	As with economic evidence, sems accurate, but having it updated regularly would ensure this	Appears to be accurate - don't have enough detailed knowledge to compare	Extremely helpful and accurate - based on local knowledge and likely contamination

Table 4.7 DSS Improvements.

DSS Aspect	Feature	Justification	Mock-Up Created?	Improvement Implemented?	Comments
General	Addition of more contextual layers (LPA boundaries, BLR sites, active developments, currently built areas, demographics, Local plans, strategic plans, utilities etc.)	Currently, this is not possible and hinders the user's ability to place the outputs in context with spatial planning relevant datasets (Planning Officers). The addition of these layers in the DSS will contextualise outputs in relation to commonly used metrics such as deprivation, LPA, wards, plans etc.	No	Yes	Some layers will be possible to add at this stage, others need to be sourced/created later in the DSS commercialisation lifecycle
Land-Use	Inclusion of 'Supporting Data' for Land-Use potential module, similar to how it is presented in the ground risk module	Currently, the land-use potential module doesn't have the supporting data behind it able to be viewed by the user, and this prevents in-depth analysis of land-use potential drivers. Allows users to explore underlying data for the land-use potential module, helping them to understand why the model has assigned a certain classification	No	Yes	
Land-Use	Inclusion of Greenbelt land into MCDA for residential assessment,	The residential LUP model now better reflects planning policy, prior to this sites within the greenbelt were being incorrectly included in the LUP assessment	No	Yes	

	additionally showstopper criteria.				
Summary Page	Move the summary page at the start to provide site overviews	This allows for a quicker high-level assessment of sites, which is preferable for users. If the user wants to, they are then able to move through the modules to dig into certain aspects in more detail.	No	Yes	
General	When flicking between DSS modules, the location and zoom are preserved, meaning that users dont have to zoom in and pan to the site they were looking at in the previous module	Currently, the DSS map windows reset to maximum zoon, when switching between modules/tabs, this improvement saves time and effort, when users are navigating DSS, and also aids in users' ability to analyse sites/areas.	Yes	No	Not technologically possible in the DSS prototyping platform
General	The ability for users to upload their own spatial data into the DSS 'on-the-fly' for visualisation alongside the module outputs	Currently doesn't allow for users to upload datasets, this improvement would allow users to contextualise DSS outputs alongside other datasets they may be working with	Yes	No	Not technologically possible in DSS prototyping platform

General	Improved user controls for controlling properties and styles of layers (e.g., ordering, transparency etc)	This DSS currently has fixed styling properties, and the display order cannot be changed, meaning that when lots of datasets are displayed at once, it can get very complicated and hard to interpret. Give users flexibility for how they want to see layers stylised, aiding they're experience.	Yes	No	Not technologically possible in DSS prototyping platform
General	The ability to for users to select multiple sites in the DSS and have a new pop-up window with direct comparison of each module output	This would allow users the ability to have multiple comparisons on-the-go during a DSS session currently the DSS only allows for the selectin of on site at a time and you have to close one comparison to view another, hindering comparison of multiple sites.	Yes	No	Not technologically possible in DSS prototyping platform
General	Self-closing pop-ups and menus	Currently, pop-ups have to be closed manually by the user and this interrupts flow and navigation when using the DSS, this improvement Improves the user experience when using the DSS.	Yes	No	Not technologically possible in DSS prototyping platform
Ground Risk	The addition of explaining notes for ground risk scores and what this means in	The DSS does not currently have an explanation of ground risk scores, leading to some confusing on what the score actually means, this improvement would help to place the score in real world context for users.	Yes	No	No necessary for prototype - will come later in DSS commercialisation lifecycle

	practicality for on the ground risk.				
Summary Page	Ability for users to export data from summary page for selected sites, this might be a summary pdf report, excel document, or spatial data attribute with DSS outputs for the site.	This would allow users to share, use and interact with the DSS outputs in different ways than just the DSS interface.	Yes	No	Not technologically possible in DSS prototyping platform
Economic Evidence	The ability for uses to define densities for sites on the fly to tailor economic information (house/flat prices) to a unique site design/plan.	This will allow users to tailor economic data to individual site/assessment densities, creating an output with greater accuracy for their assessment. Currently, the densities are fixed and a flat density across the site creating economic estimation that are not always accurate for sites, especially large sites.	Yes	No	Not technologically possible in DSS prototyping platform
General	The development of detailed instruction manual and training session for	In the user-testing sessions, guidance on how to use the DSS was provided with in-person help from workshop convenors. A detailed user manual would allow users to learn how to	N/A	N/A	No necessary for prototype - will come later in DSS commercialisation lifecycle

	clients/users of the DSS	use the DSS in their own time and away from the guided sessions.			
General	Improved DSS performance (fast layer loading) - likely to happen in fully deployable application	In the workshop the internet connection was very slow, leading to frustration when using the DSS, a better connection and more efficient performance will improve the user experience when using the DSS.	N/A	N/A	Not technologically possible in DSS prototyping platform
General	New add-in module capabilities (i.e., for renewable energy potential of sites and areas - D4S?)	This would allow users to incorporate different assessment aspects, this is something that would have to be developed on a case-by-case basis, currently the DSS is 'fixed' with the three original modules.	N/A	N/A	No necessary for prototype - will come later in DSS commercialisation lifecycle
Land-Use	Modifying land-use potential output to include ground risk into land-use potential assessment	This would allow land-use potential assessments to also account for ground risk i.e., Areas of high ground risk less preferential for residential	N/A	N/A	The scope of the DSS is to assess for land-use potential factors, and keep ground risk as a separate part of the DSS 'flow' this kind of judgment is applied by the user/expert at a later stage

Land-Use	Consideration of current land-use in land-use potential assessment	If a site is already housing, it is unlikely to be developed as greenspace, despite high theoretical spatial planning suitability.	N/A	N/A	The scope of the DSS is to assess all post-industrial land for all development types, this kind of judgment is applied by the user/expert at a later stage

4.8.1 Economic Evidence methodology

This section outlines the methodology used to create two outputs from the Economic Evidence module of the DSS; estimated new build property sale price data, and estimated land value data.

4.7.1.1 Methodology for Estimated New Build Property Sale price data

4.7.1.1.1 Datasets created

1. Estimated new build house total sale for all unit's price per site
2. Estimated new build flat total sale for all unit's price per site
3. Average House price by LSOA for Post-industrial land
4. Average House price per m^2 by LSOA for Post-industrial land
5. Average Flat price by LSOA for Post-industrial land
6. Average Flat price per m^2 by LSOA for Post-industrial land

4.7.1.1.2 Methodology for estimating New Build Property Sale Price

These datasets were created by combining three different publicly available datasets: *Price paid data* & *House price Index* data from HM Land Registry; and *Energy Performance certificate data* from Department for Levelling Up, Housing & Communities. This is because EPC data contains a record of property floorspace in m^2. This data is then merged with price-paid data to calculate the price paid per m^2 of property. These figures of the total price paid and the price paid per m^2 were then adjusted to present-day values using the House price index data. This was achieved by multiplying the values by the increase in house price index. This methodology was developed by Three Dragons Ltd. (Three Dragons, 2023), a consultancy specialising in viability and housing and development economics. Three Dragons Ltd. shared this methodology with this project.

Next, the Price Paid and EPC data to create these outputs were downloaded. The data range selected was 2016 – 2021, and the area selected was that of the constituent LPAs of the Liverpool City Region Combined Authority: Halton, Knowsley, Sefton, Liverpool, St. Helens, and Wirral. The data was downloaded from the respective data download portals using the criteria above to filter. The data was downloaded in CSV format which was then opened in Microsoft Excel. Prior to processing, the datasets were opened and re-saved as Excel documents and formatted as Excel tables for their subsequent use in the fuzzy-merge process.

To match the price paid data to EPC data, the address fields were used. However, because of the mixed provenance of the data, there were often inconsistencies found in spelling, formatting, and input errors, meaning that matching the addresses using conventional methods would have resulted in many records not being matched. For example, '64 Haldon Street, Apartment 5' might be recorded as 'APPARTMENT FIVE, 64 HALDON ST' in different datasets. To overcome this, a fuzzy-merge method was used. The fuzzy-lookup add-in for Excel was used for matching textual data in Microsoft Excel. It was used to fuzzy join similar rows (based on address) between two different tables. This add-in scores the returned records on similarity from which an additional matching process was re-run several times to match results that had initially scored low similarity. This matching process was undertaken for houses (8,180 records) and flats (5,335 records). Once the price paid records had been matched with the correct EPC record, the price paid per m^2 and HPI adjustment of price paid value was created as follows:

HPI Adjusted price = (Current HPI Value / HPI Value at the time of transaction) * price Paid at time of transaction

HPI Adjusted price Paid per m^2 = HPI Adjusted price / Area (m^2)

The file was streamlined by removing redundant fields, such as duplicate addresses and postcodes found in both the Energy Performance Certificate (EPC) and price paid data, along with other irrelevant fields. The price paid data was then converted into a spatial data format using the ArcGIS World Geocoding service tool in ArcGIS Pro. This involved uploading the data as a table into ArcGIS Pro and running the geocoding service to create a point dataset with 13,515 records attributed to the table. The newly created data were spatially joined multiple times to the

-study sites with a 1 km tolerance, taking an average of the relevant House Price Index (HPI) adjusted price paid value as the summary field to produce datasets 1 and 2. Similarly, the newly created data were spatially joined multiple times to Lower-layer Super Output Area (LSOA) polygons, taking an average of the relevant HPI adjusted price paid value as the summary field to produce datasets 3-6. To compute the Estimated New Build total sale price per site for houses and flats, a new field was created using the ArcGIS Pro Field Calculator.

4.7.1.2 Land Value Estimates

4.7.1.2.1 Datasets Created

This data theme consists of the following datasets that were specifically created for this project:

1. Estimated Site Value for study sites - Residential
2. Estimated Site Value for study sites - Industrial
3. Estimated Site Value for study sites - Office (Central Business District)
4. Estimated Site Value for study sites - Office (Out of town)
5. Estimated Site Value for study sites - Agricultural

6. Estimated Land Value per hectare by LPA for post-industrial land - Residential
7. Estimated Land Value per hectare by LPA for post-industrial land - Industrial
8. Estimated Land Value per hectare by LEP for post-industrial land - Office (Central Business District)
9. Estimated Land Value per hectare by LEP for post-industrial land - Office (Out of town)
10. Estimated Land Value per hectare by LEP for post-industrial land – Agricultural

4.7.1.2.2 Methodology for Land Value Estimation

To produce these outputs two datasets were downloaded:

1. Land value estimates for policy appraisal 2019 from the Valuation Office Agency. The estimated values provided are in £ per Hectare.
2. Local Planning Authority (LPA) and Local Enterprise Partnership (LEP) Polygons from data.gov.uk

Using ArcGIS Pro attribute table, the land value estimates were appended to the LPA and LEP polygons and then clipped to the area of post-industrial land. This created datasets 5 – 10. Using the spatial join function in ArcGIS Pro, the land-value data was joined to the case-study polygons taking the land value as the summary field. This was undertaken multiple times to allow the production of datasets 1- 5 presented at the start of the section. To create a value for the estimated site value the ArcGIS 'Field Calculator' was used to create a new field creating the site value for the 5 land-use types using the following formula:

Estimate Site Value = Estimate Land Value per Hectare * Area of Site in Hectares

The layers were then configured in individual ArcGIS Pro. This included grouping the layers into themes (by site and by area) and defining the symbology and attribute field

names. Following this the ArcGIS Map containing the Estimated Land Value data, which was then uploaded to ArcGIS Online using the built-in upload tools.

4.7.1.3 References:

Three Dragons, 2023. Three Dragons | Independent Consultancy [WWW Document]. URL https://www.three-dragons.co.uk/ (accessed 2.14.23).

4.8.2 Improved user interface mock-ups

This appendix presents mock-ups of potential future improvements to the DSS. These were identified and discussed with stakeholders during the user testing process (section 4.3.2).

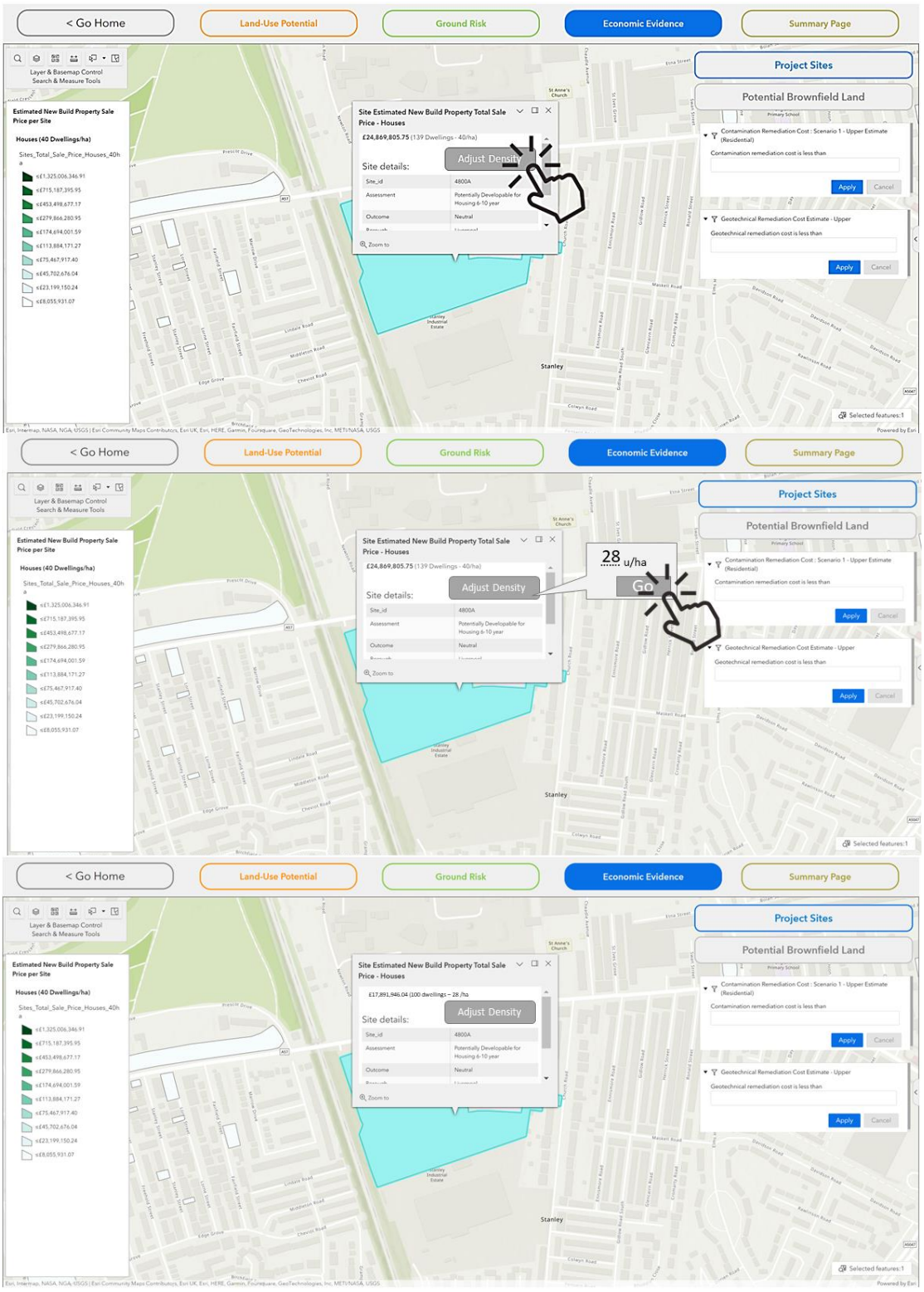


Figure 4.13 Improvement mock-up showing how densities for economic evidence outputs would be adjusted in real-time within the DSS interface.

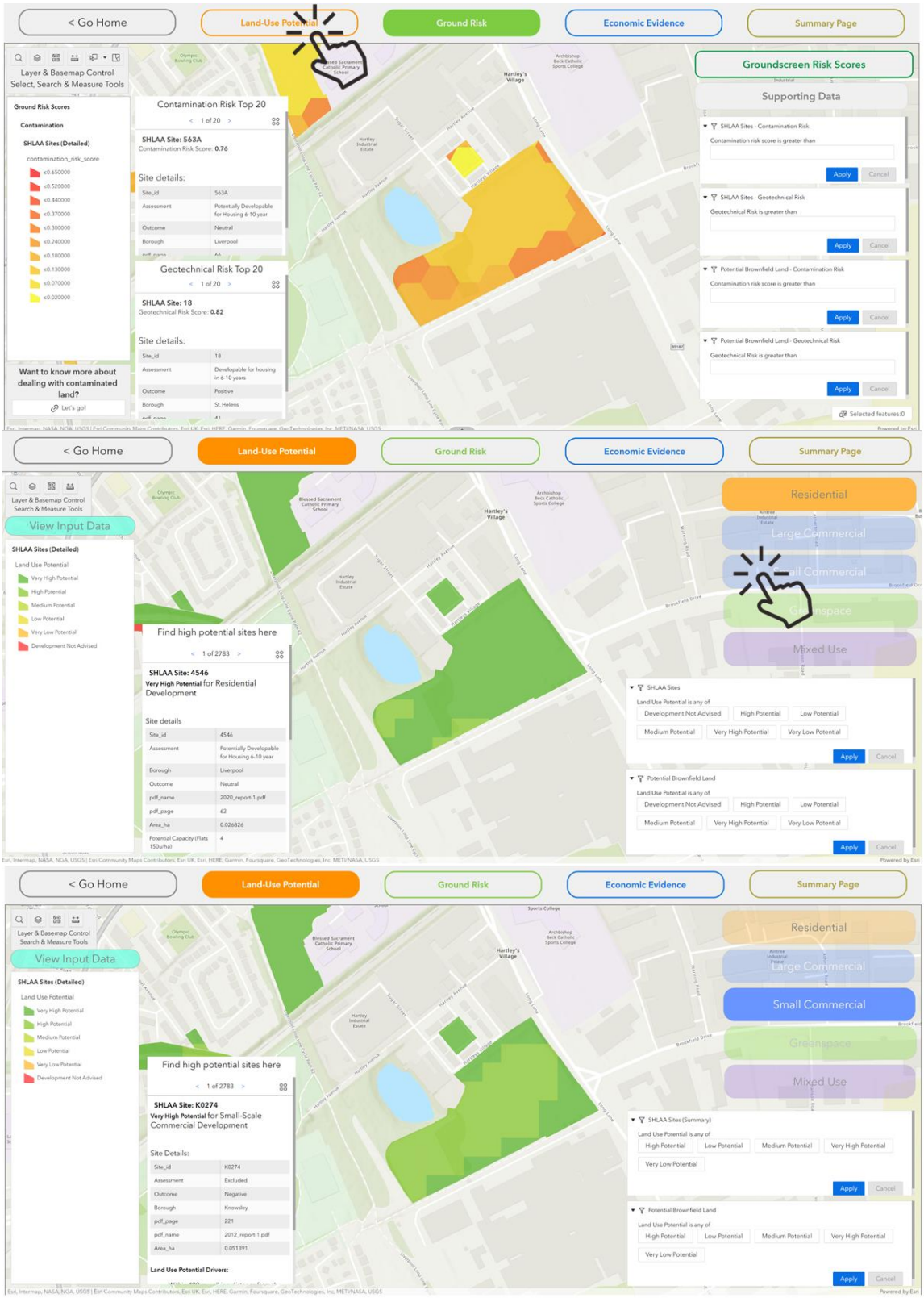


Figure 4.14 Improvement mock-up showing how location and zoom would be preserved when moving between DSS modules

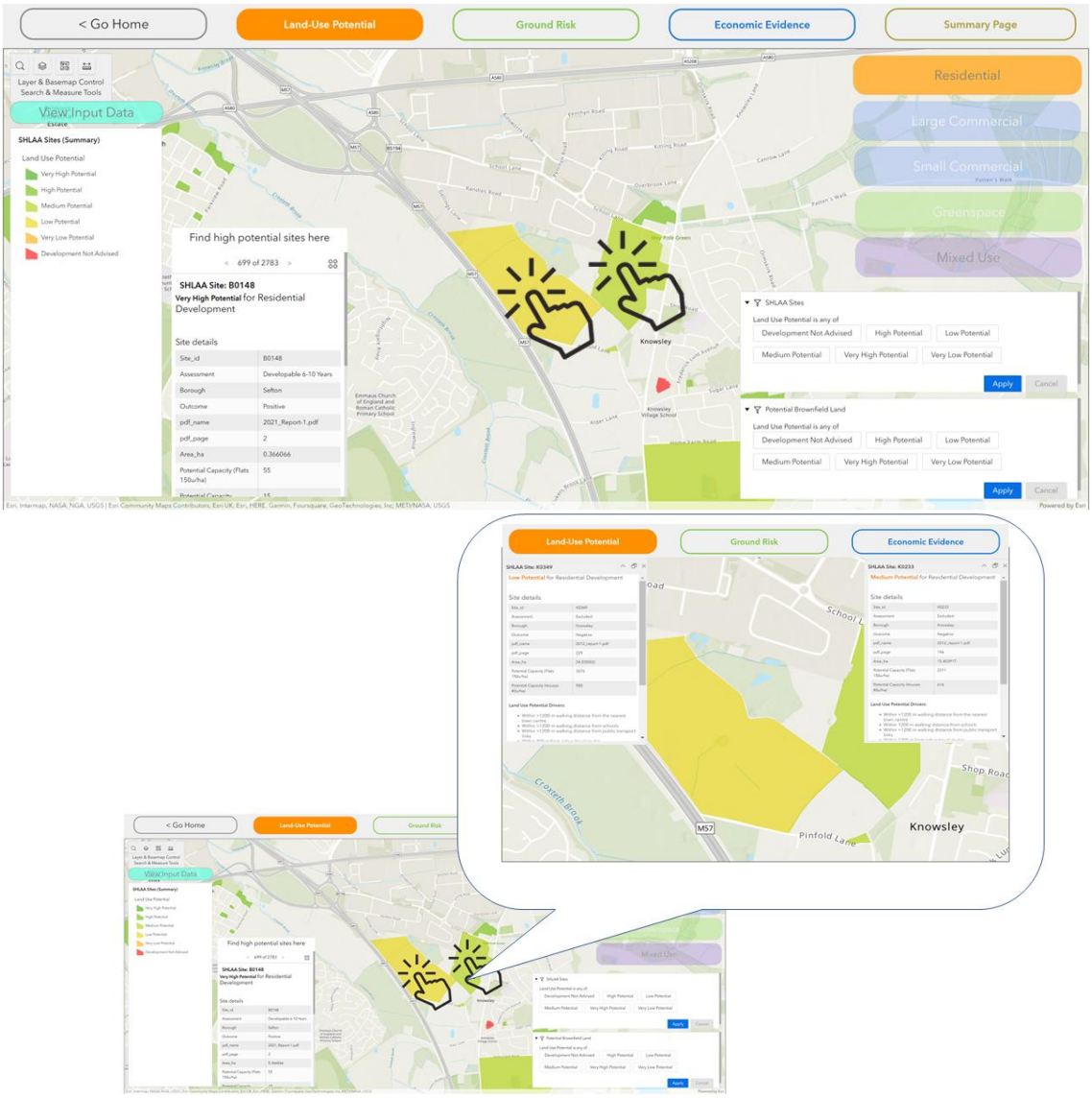


Figure 4.15 Improvement mock-up showing the selection and side by side comparison of multiple sites at once

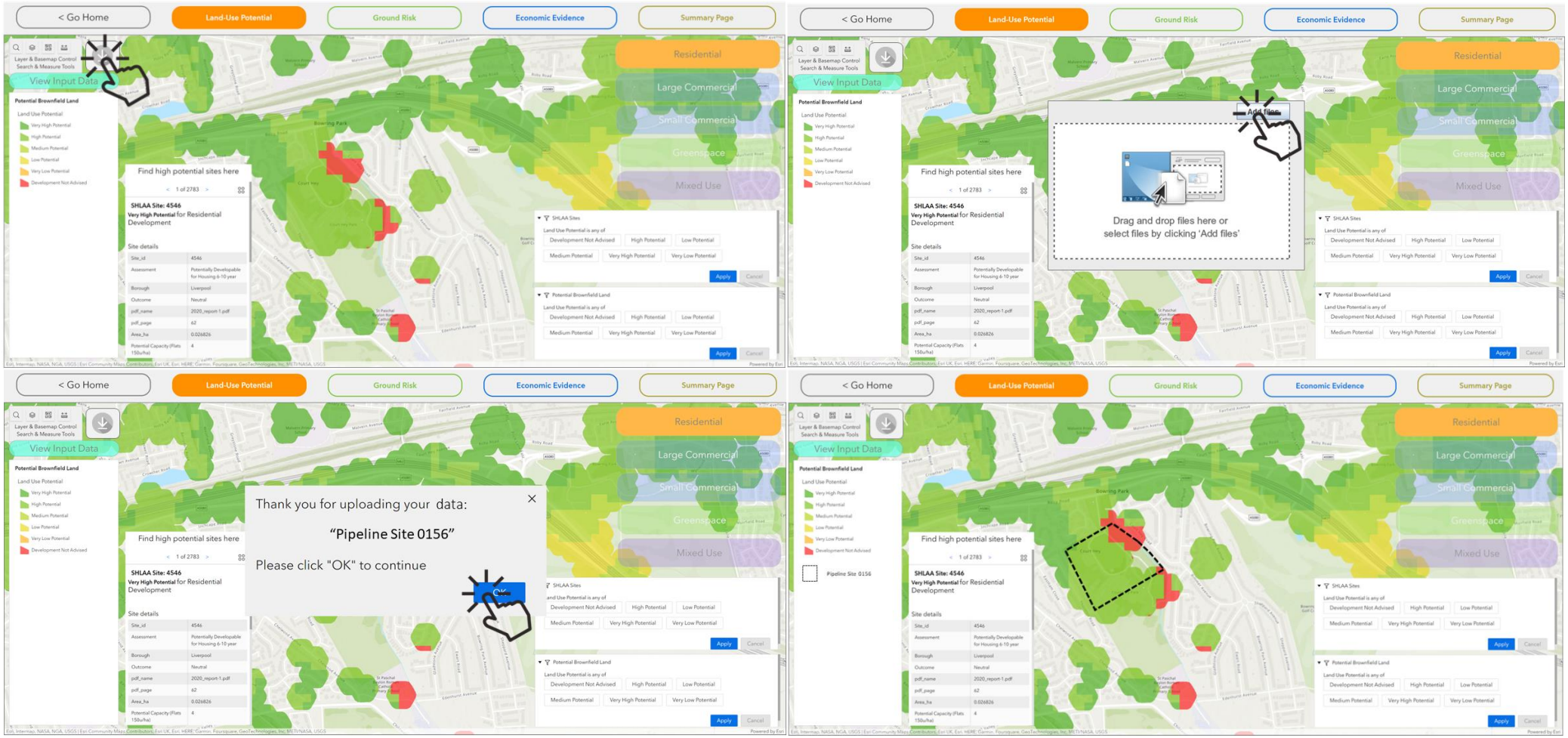


Figure 4.16 Improvement mock-up showing the process for how users would upload their own spatial data into the DSS in real-time

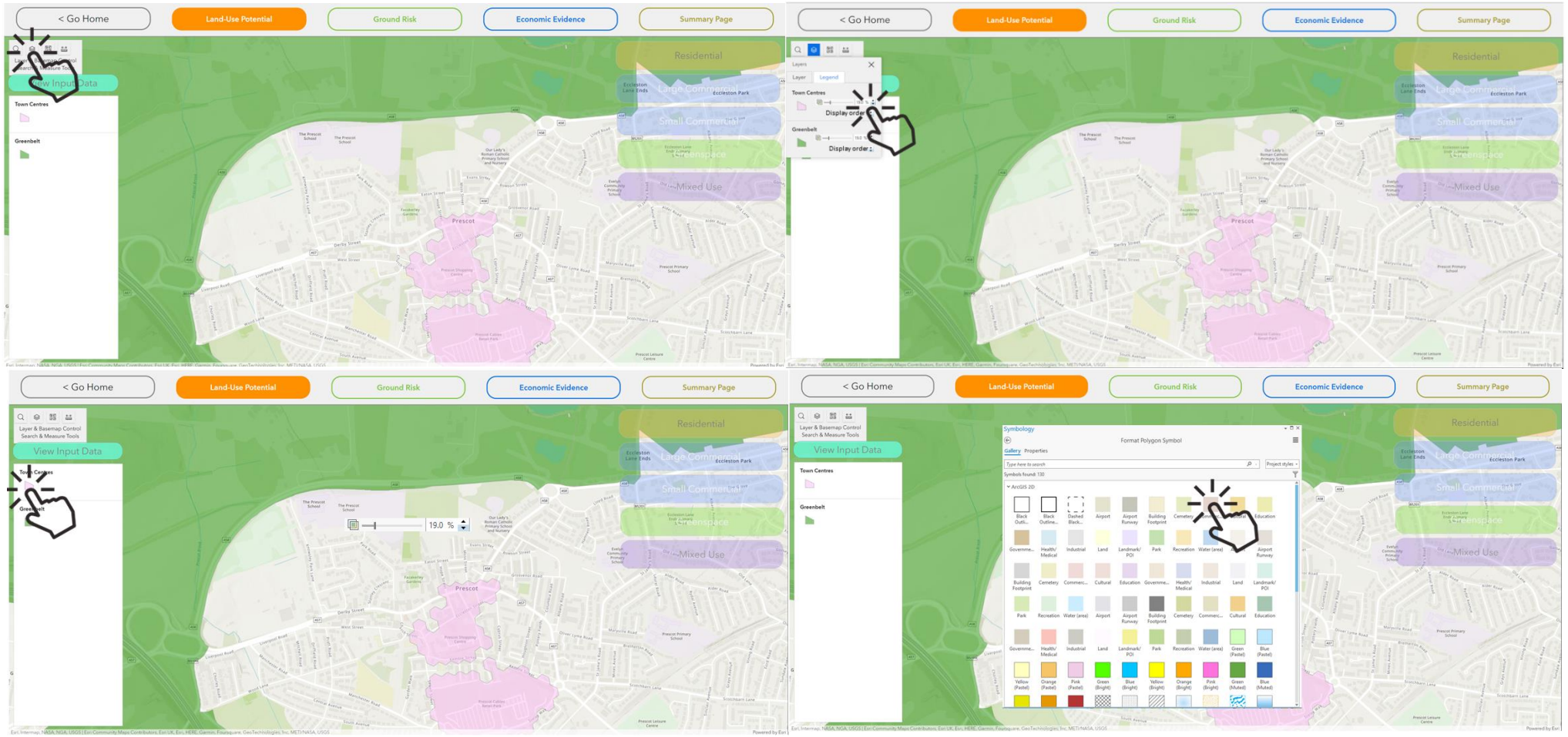


Figure 4.17 Improvement mock-up showing the process for uses adjusting display order and transparency of layers within the DSS interface in real-time.

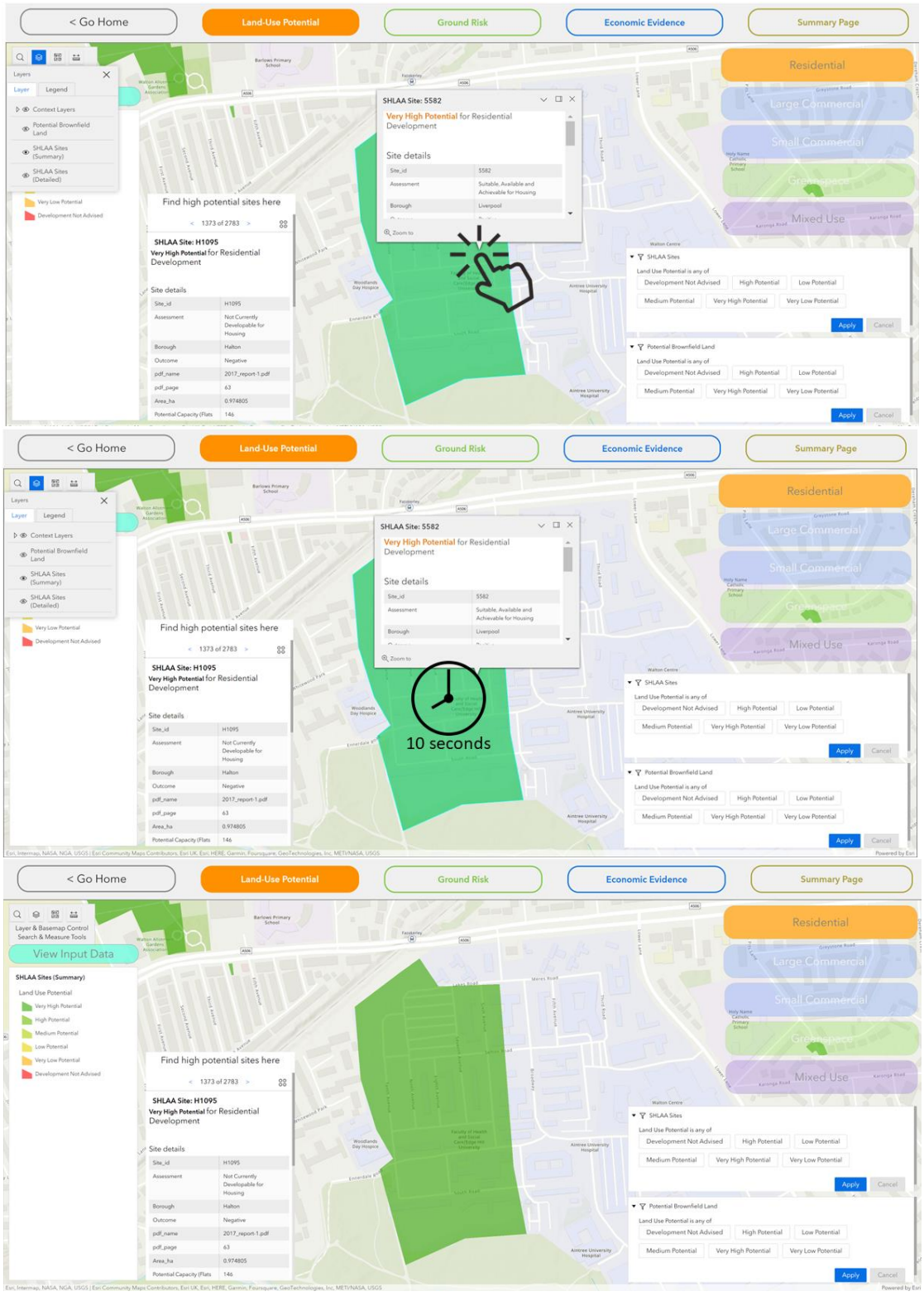


Figure 4.18 Improvement mock-up showing the process for self-closing pop-ups

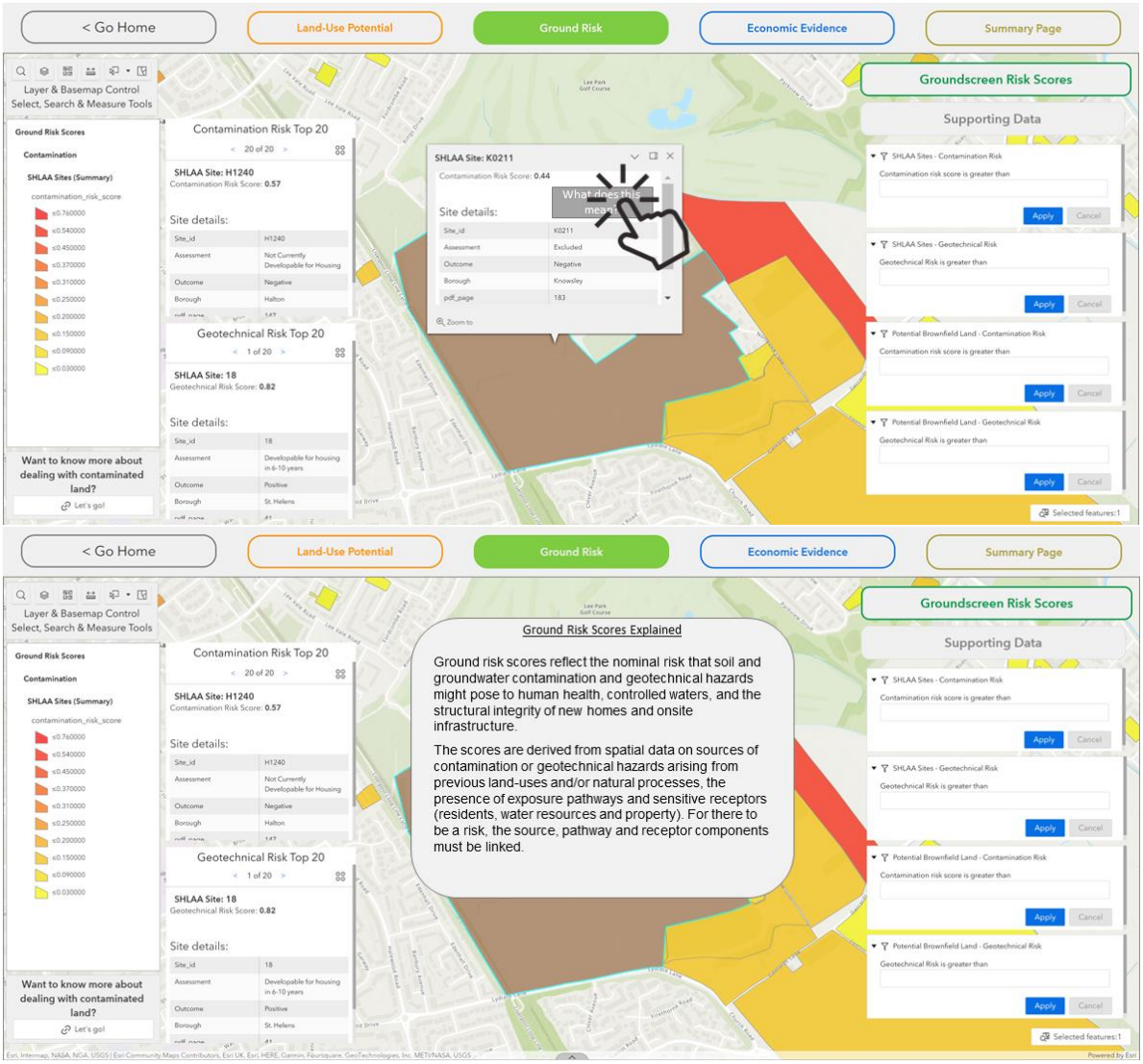


Figure 4.19 Improvement mock-up showing an explanatory pop-up for ground risk scores

Figure 4.20 Improvement mock-up showing the process of exporting results from the summary screen

5 FROM DATA TO DECISIONS: EMPOWERING BROWNFIELD REDEVELOPMENT WITH A NOVEL DECISION SUPPORT SYSTEM

Ellis B. Hammond[1, 2], Frederic Coulon[2], Stephen H. Hallett[2], Russell Thomas[3], Alistair Dick[4], Drew Hardy[5], Mark Dickens[6], Emma Washbourn[6], Darren J. Beriro[1*]

[1]British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK.

[2]School of Water, Energy and Environment, Cranfield University, Cranfield, MK43 0AL, UK.

[3]WSP, Kings Orchard, 1 Queen St, Bristol, BS2 0HQ, UK.

[4]Groundsure, Nile House, Nile St, Brighton, BN1 1HW, UK.

[5]LandTech, 9 Appold St, London EC2A 2AP, UK

[6]Liverpool City Region Combined Authority, 1 Mann Island, Liverpool, L3 1BP, UK.

Abstract: This research evaluates a novel decision support system (DSS) for planning brownfield redevelopment. The DSS is implemented within a geographical information system that contains spatial data which informs three modules including land use suitability, economic viability, and ground risk. Using the DSS, an evaluation was carried out on 31,942 ha of post-industrial land in the Liverpool area. The representativeness and credibility of the DSS outputs were evaluated through user testing with local stakeholders. Results show that the DSS outputs closely match real-world land use planning decision making outcomes. Our study 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 process of conducting repeatable assessments of land suitability and viability. This research has important implications for planning policy and the adoption of digital tools in land use planning in the UK and sustainable development objectives globally.

Keywords: Land use Planning, Stakeholder Engagement, Digital Tools, Urban Land

5.1 Introduction

Land is a finite resource, with urban land development posing significant challenges (Amato et al., 2016; DSIT and Geospatial Commission, 2023). Some 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 (Homes 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 sites across the EU (Van Liedekerke et al., 2014), 500,000 sites in the United States (Green, 2018), and an estimated 23,000 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 developers and land use

planners are encouraged to consider all possible land uses when making development plans, 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 (DLUHC and MHCLG, 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 carry out a review of available land 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 (HM Government, 2017).

Land use planning for brownfield redevelopment is a complex and multifaceted process that involves engaging with, and where possible meeting the needs of, stakeholders. Decisions should be underpinned with 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 developments, 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 can provide a more accurate and easier-to-understand representation of the local area, allowing planners to make more informed decisions. 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), as are digital consultation and engagement tools, used 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 (Hammond et al., 2023; Marcomini et al., 2009; Pettit et al., 2018). These tools are designed to enhance the value of data and information and increase the understanding of an issue or problem for planners, developers, contractors, and their advisors, often through decision analysis or spatial visualisation of the data. There are numerous examples of brownfield DSS and PSS 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., 2023, 2021; Pettit et al., 2018).

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 redevelopment and land use planning. These authors identified potential areas of improvement, particularly: the usability of the system, reducing excess complexity in terms of the input decisions users must make, increasing functionality to match users/stakeholder expectations, and enhancing interpretability by optimising the number of variables present within the decision analysis and adopting participatory approaches to development with the intended user base.

In a study by Hammond et al., (2024) (Chapter 4), a novel DSS designed for early-stage city-region level land use planning and brownfield redevelopment is introduced. The primary focus of this research is to assess the effectiveness of the DSS within the context of the Liverpool city region, UK; an area where brownfield redevelopment is crucial to support local development. Our research objectives are: (1) to verify the DSS outputs using qualitative and quantitative methods, and (2) to evaluate the potential influence of the DSS on land use planning by facilitating rapid assessments and evaluations of brownfield land suitability and viability.

5.2 Methods

5.2.1 Overview of the DSS

The methodology used to create the DSS and its outputs is described in detail in Hammond et al., (2024) (Chapter 4). In summary, the DSS has three modules, contained within an ESRI ArcGIS Online user interface (Figure 5.1): (1) land use potential (LUP) for residential, commercial, greenspace, and mixed-use, which presents an assessment of a brownfield site/areas spatial planning potential, derived from multi-criteria decision analysis (MCDA), (2) ground risk, which presents soil and groundwater contamination and geotechnical risk scores also derived using 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 50m grid 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 or via a portfolio of user-defined sites, where each site is attributed with the outputs from each module (Hammond et al., 2024) (Chapter 4). For each 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 (Figure 5.2). These functions allow the user to compare differences in scores within and between sites.

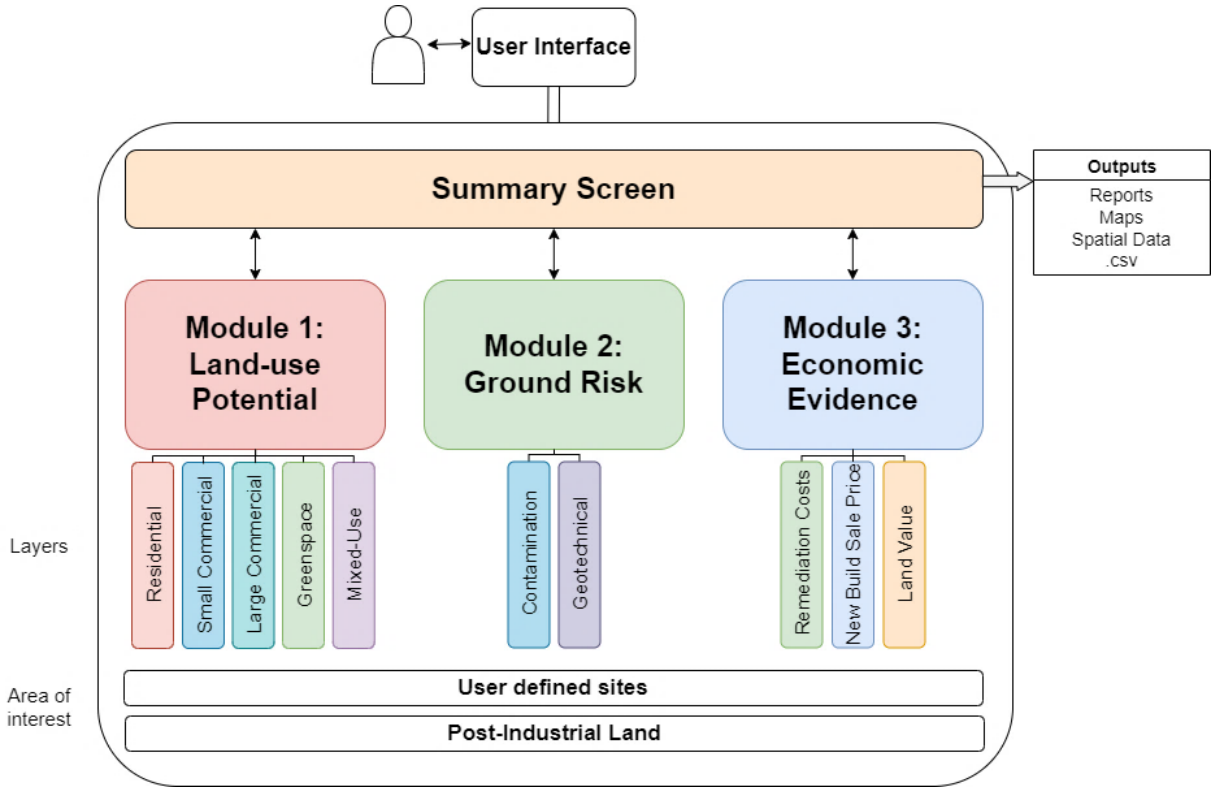


Figure 5.1 DSS Overview, showing data layers within the three modules (Land use Potential, Ground Risk, Economic Evidence).

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., 2024) (Chapter 4). The ground risk scores were provided for this research by Groundsure as part of their 'Groundscreen' data product (Groundsure, 2023). The economic evidence module comprises three datasets: (1) estimated remediation costs for contamination and

geotechnical hazards (also from ‘Groundscreen’), (2) estimated land value (MHCLG 2020a), and (3) estimated new build property total sale price (derived using recent transaction data (HMLR, 2023)) (Hammond et al., 2024) (Chapter 4).

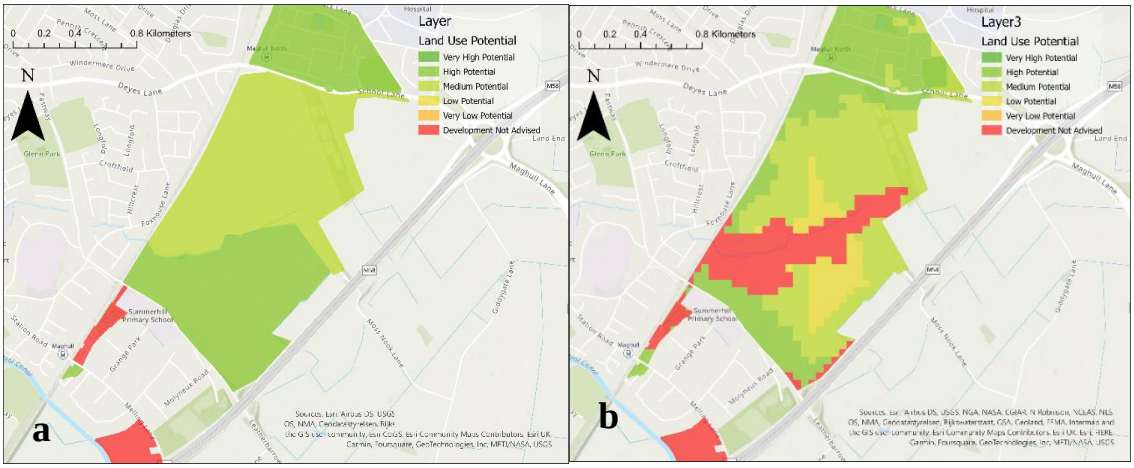


Figure 5.2 Example of site summary (a) and site detailed (b) views. Basemap attribution: *Esri, Intermap, NGA, USGS, NLS, NCEAS, OS, NMA, FEMA, Geoland, Airbus DS, Geodatastyrelsen, Rijkswaterstaat, Esri Community Map Contributors, Esri UK, HERE, Garmin, Foursquare, GeoTechnologies Inc, METI/NASA.*

5.2.2 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) (Figure 5.3). All DSS outputs were generated for these study sites and analysed using ESRI ArcGIS Pro tools to identify trends and patterns to understand the development potential of the area. Any reasons for underlying similarities/differences for LUP classifications, ground risk scores, and economic evidence values were investigated.

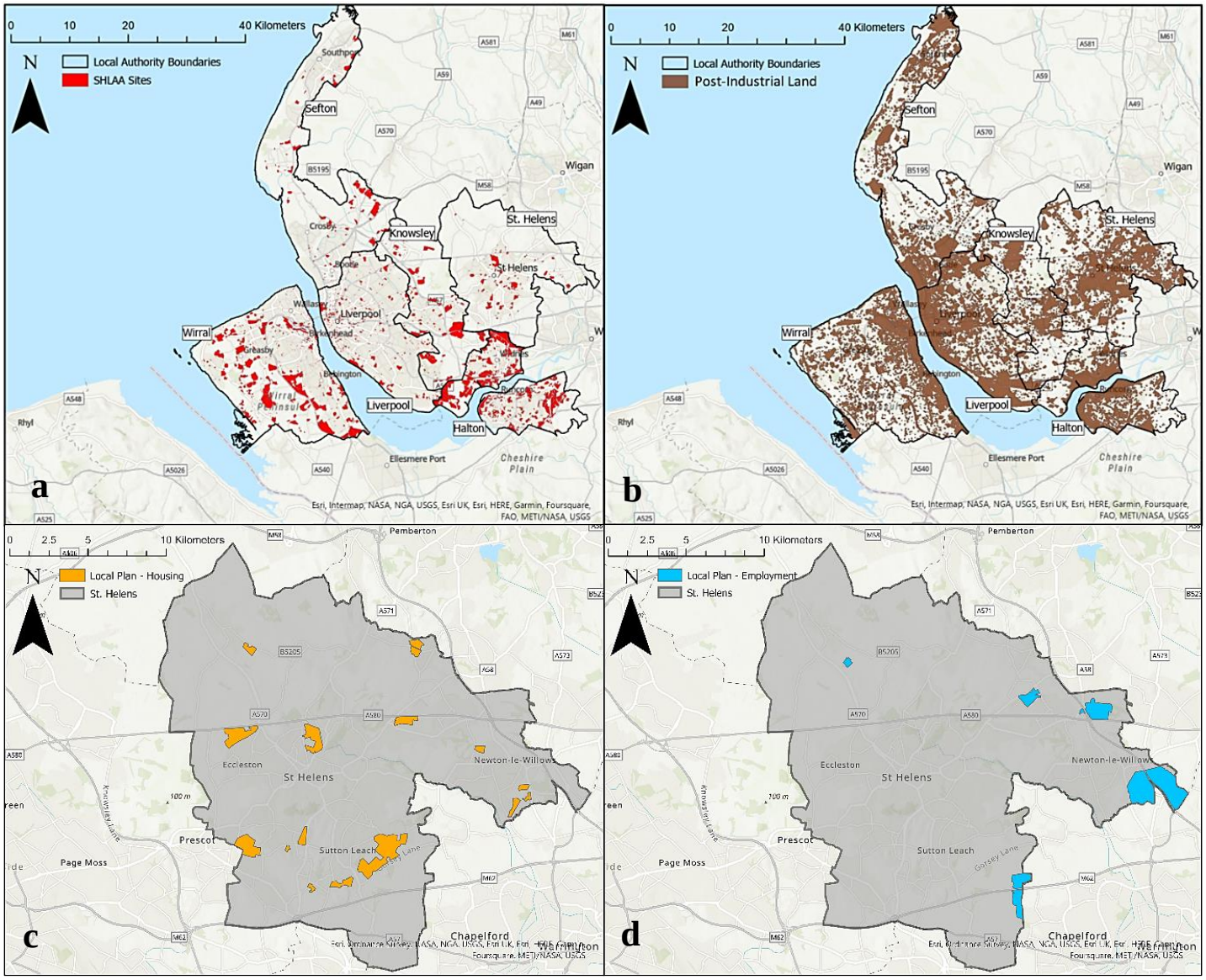


Figure 5.3 Liverpool city region distribution of SHLAA sites (a), post-industrial land areas (b), and St Helens local plan development areas (c, d). Basemap attribution: *Esri, Intermap, NASA, NGA, USGS, Esri Community Map Contributors, Esri UK, HERE, Garmin, Foursquare, GeoTechnologies Inc, METI/NASA.*

Post-industrial land for the city region comprises an area of approximately 31,942 hectares (~ 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 (Figure 5.3). Post-Industrial Land (PIL) was identified in the GIS using historical land use data to determine previously developed land; this comprises 43.5% of the total Liverpool city region area (Hammond et al. 2024) (Chapter 4).

The SHLAA land comprises 2,783 sites (6,185.3 ha) (Figure 5.3) and was provided in GIS format for this research by *LandTech*. 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 5.1).

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) (Figure 5.3). These areas were digitised into GIS layers and used to produce DSS outputs.

Table 5.1 Size and distribution of study sites and post-industrial land within the Liverpool City Region Authority.

Local Authority	**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

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 (Figure 5.4).

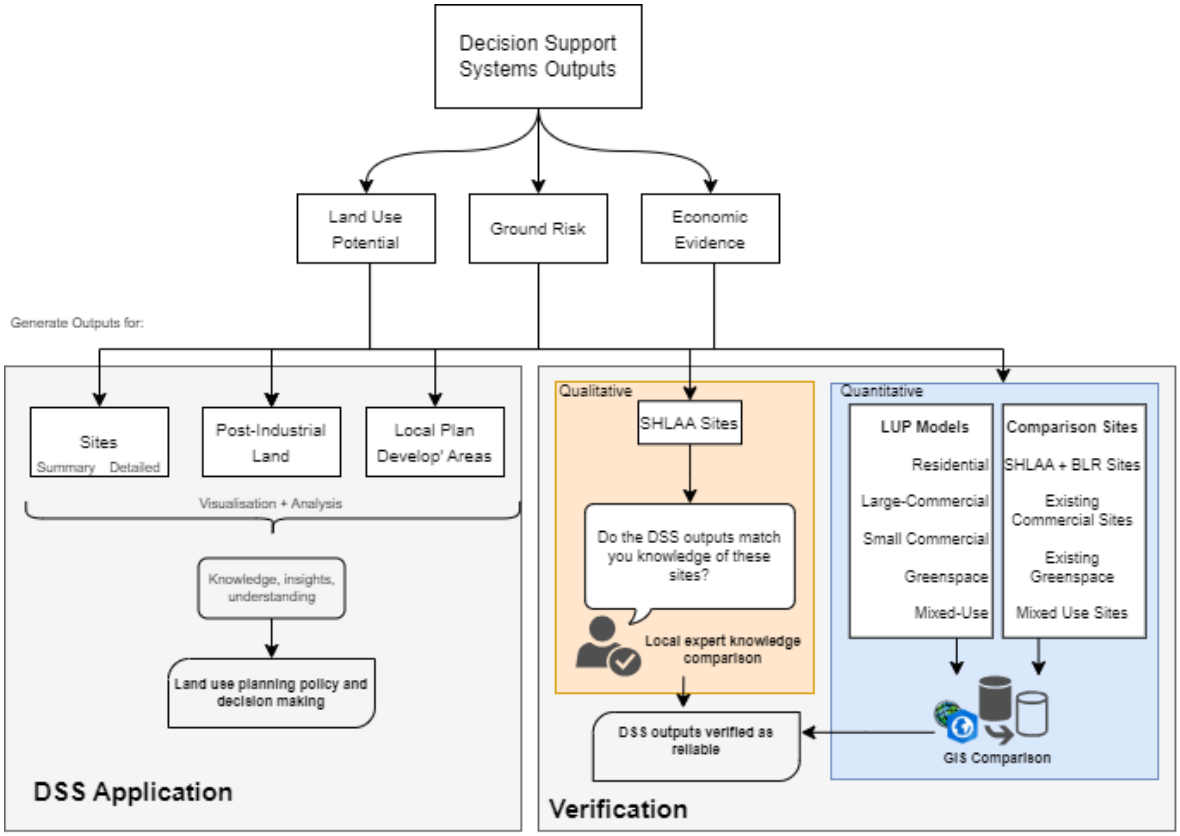


Figure 5.4 Summary of methods for case-study application and verification of DSS outputs.

5.2.3 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 5.2). The verification process was conducted in two stages: (1) real-world comparison sites were obtained or 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 six LUP categories were reclassified as binary outcomes

(positive/negative), (4) a GIS-based comparison was carried out between the outcome of LUP models and real-world planning decision outcome for each comparison sites.

For residential land use potential, comparison was undertaken using two publicly available potential housing datasets: Brownfield Land Register (BLR) sites (n = 392), and SHLAA sites (n = 2,783). 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 5.2). 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.

Table 5.2 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.

The DSS LUP scores range from 0 to 1 (Table 5.3). 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 5.3). For the SHLAA and BLR sites, the positive/negative classification was used to compare the DSS results with the formal LPA SHLAA outcome results.

Table 5.3 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	

Using a GIS attribute table, 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 5.3. 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.

5.2.4 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 expert knowledge of those sites. This user-based testing approach was undertaken during a facilitated workshop with 15 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

of the real-world outcome/condition of the site. Feedback was recorded using responses to a standardised set of questions and notes from discussions (Table 4.6, Appendix 4.8).

The agreement between the DSS outputs and the experts' expectations and knowledge of the sites was assessed. 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 be accurate and representative of current real-world conditions.

This mixed-methods approach to verification, and specifically the qualitative verification used, allows for the research to elicit valuable feedback and understanding from the users who took part in testing. This feedback proved to be very useful and informative in assessing how well the DSS performed in the user testing (Hammond et al., 2024) (Chapter 4) and also here in this paper (Chapter 5) the expert *sense-checking* of the DSS outputs.

5.3 Results

5.3.1 Liverpool city region

The Liverpool City Region Combined Authority (LCRCA) area (Figure 5.5) 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 has a greater prevalence of deprivation than the UK national average across all domains of deprivation (MHCLG, 2019), with 1 in 3 of LCR's 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.

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

Figure 5.5 The Liverpool city-region and its six constituent Local Authorities.

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. Hammond et al. (2024) (Chapter 4) describe how multiple engagement sessions with stakeholders from LCRCA were conducted to develop the usability and functionality of the DSS.

5.3.2 Quantitative verification of land use potential

5.3.2.1 Residential land use

There is a significant level of agreement between the LUP model and actual residential sites (Table 5.4). The verification process revealed that the land use potential model 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 (Table 5.4, Table 5.5).

Table 5.4 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

Table 5.5. Confusion matrix of results from verification of residential land use potential GIS-MCDA model when positive outcomes are assigned to medium potential or above. The figures displayed indicate the count of sites for each class.

		SHLAA Sites (Summary)		SHLAA Sites (Detailed)	
		Predicted		Predicted	
		Positive	Negative	Positive	Negative
Actual	Positive	2,617	1,837	2,699	1,922
	Negative	166	946	84	861

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 because of 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 because of 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.

5.3.2.2 Other land use types

Results also show a very high level of agreement between the other LUP models and verification test sites (Table 5.6). 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.

Table 5.6 Result from verification of other land use types.

Large Commercial	
Site Type	Agreement (%)
Site Summary	97
Site Detailed	97
Small Commercial	
Site Type	Agreement (%)
Site Summary	99
Site Detailed	99
Greenspace	
Site Type	Agreement (%)
Site Summary	100
Site Detailed	97
Mixed-Use	
Site Type	Agreement (%)
Site Summary	99
Site Detailed	96

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.

5.3.3 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 5.7). 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 5.7) 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's local expert knowledge of 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.

Table 5.7 Results from qualitative verification of the DSS by local experts.

Session	Study site ID	Does the output match your knowledge/experience?		
		Land Use Potential	Ground Risk	Economic Evidence
Session 1 – Land Use Planners	WI01	✓	✓	✓
	HI532	✓	✓	✓
	111	✓	✓	✓
	B0205	✓	✓	✓
	2553	✓	✓	✓
Session 2 – Housing & Energy Specialists	2659	✓	✓	✓
	4546	✓	✓	✓
Session 3 – Housing, Planning, and Investment Specialists	4078	✓	✓	✓
	2553	✓	✓	~
	S0260	✓	✓	✓
Session 4 – Combined Authority Officers	1553	✓	✓	✓

5.3.4 Evaluation of post-industrial land and study sites

5.3.4.1 Land use potential

The DSS LUP potential module was applied to post-industrial land and study sites in the Liverpool city region (Table 5.8).

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 (Figure 5.6). This restricts the suitability of large areas of the city region for residential development. However, for the portfolio of 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., 2024), 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 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.

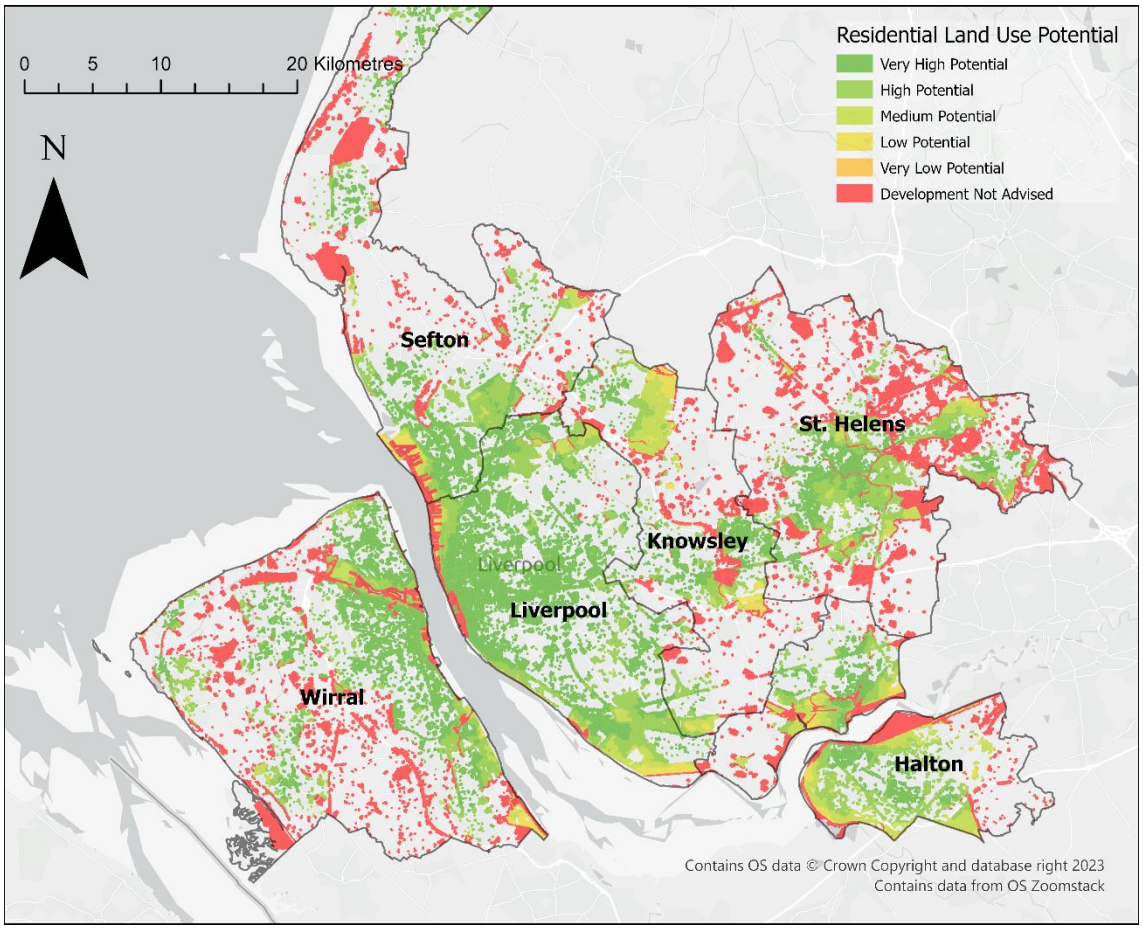


Figure 5.6 Residential land use potential for LCR post-industrial land.

Table 5.8 Land use potential assessment.

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
Note: values are rounded to the nearest whole number						

5.3.4.2 Ground risk

Ground risk scores for the Liverpool City Region are presented in Table 5.9. 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 0.1 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

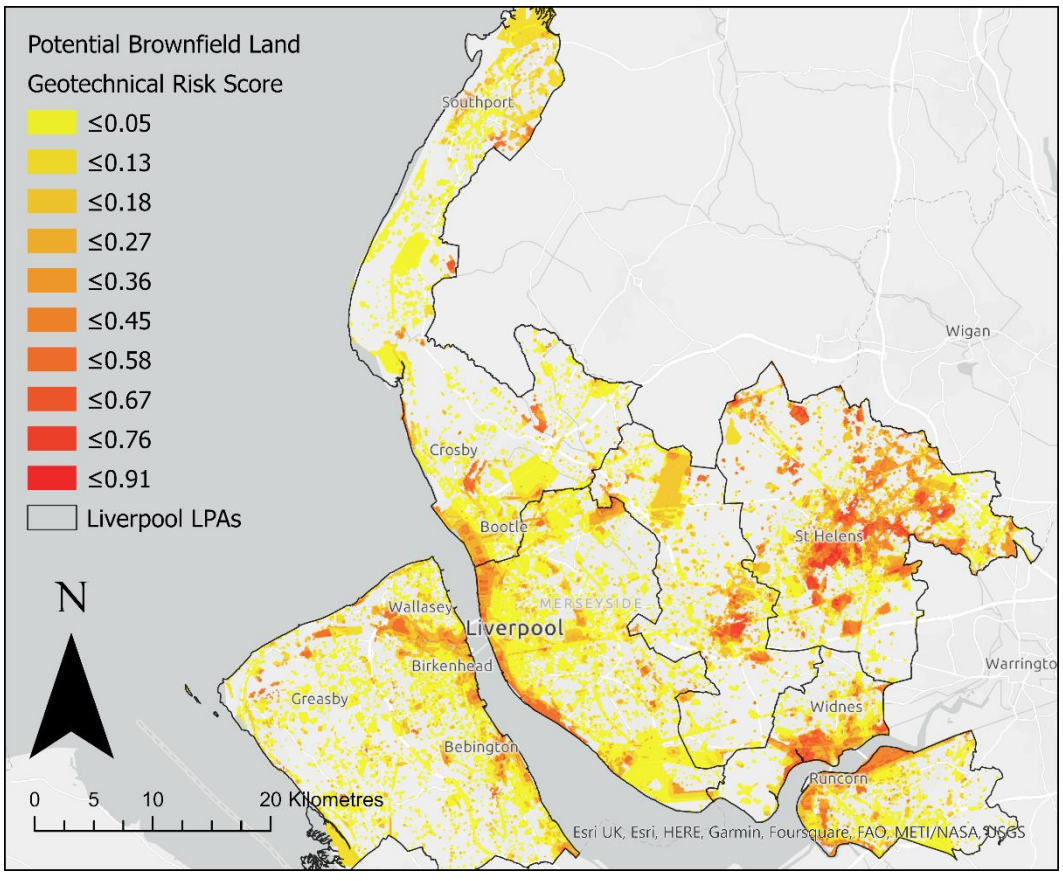


Figure 5.7 Distribution of contamination ground risk scores for post-industrial land in the Liverpool city region.

considerably higher risk scores than the rest of the city region. Figure 5.7 illustrates the distribution of contamination risk scores for post-industrial land across LCR.

Table 5.9 Ground risk scores for the Liverpool City Region.

	Post-industrial land	
	Contamination	**Geotechnical**
Minimum	0	0
Maximum	0.87	0.91
Mean	0.1	0.12
	Study Sites (Summary)	
	Contamination	**Geotechnical**
Minimum	0	0
Maximum	0.75	0.82
Mean	0.12	0.12
	Study Sites (Detailed)	
	Contamination	**Geotechnical**
Minimum	0	0
Maximum	0.75	0.82
Mean	0.07	0.1
	St Helens Local Plan - Housing	
	Contamination	**Geotechnical**
Minimum	0	0
Maximum	0.82	0.73
Mean	0.06	0.11
	St Helens Local Plan - Employment	
	Contamination	**Geotechnical**
Minimum	0	0
Maximum	0.46	0.51
Mean	0.04	0.09

5.3.4.3 Economic Evidence

A summary of the Economic Evidence module results for the study (SHLAA) sites is provided in Table 5.10. 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 (Figure 5.8). The distribution of estimated values for 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*, within the top 20% most deprived area in LCRCA, the average house price per m^2 is £488 per m^2, placing it in the bottom 5% in LCRCA in terms of

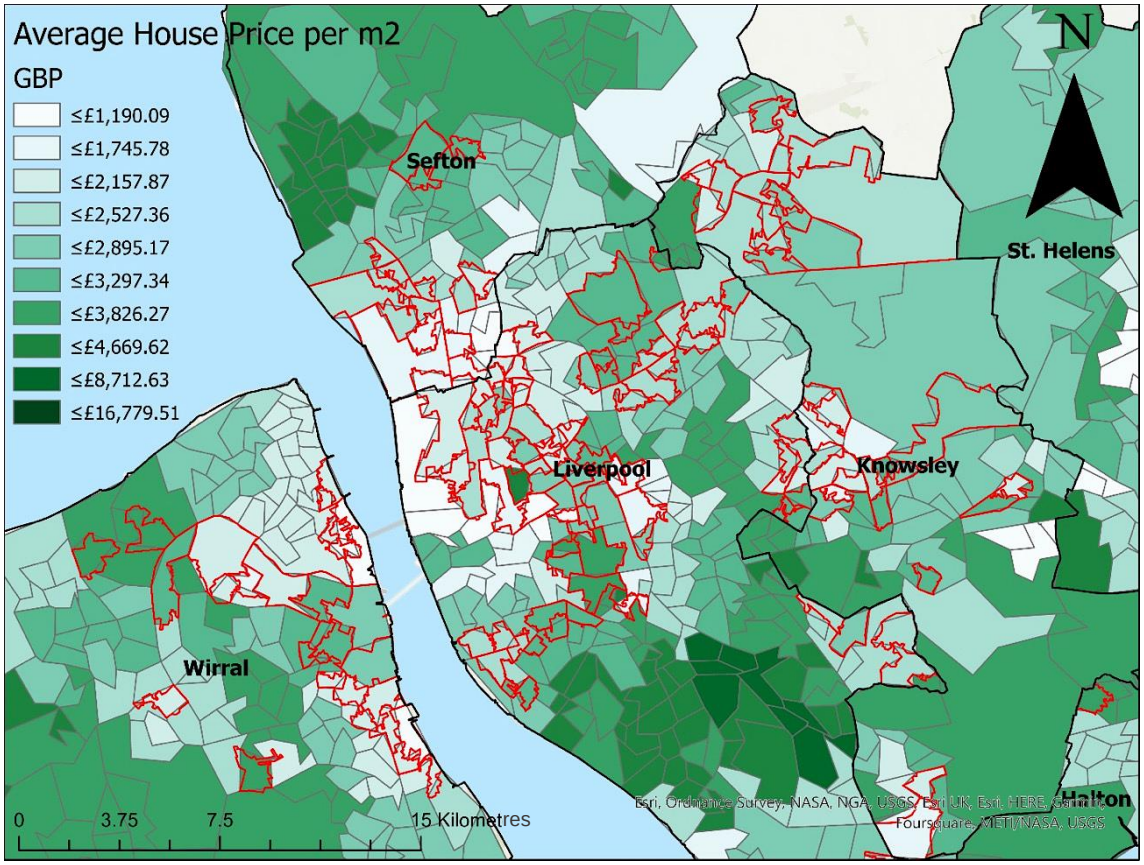


Figure 5.8 LCRCA post-industrial land new build house prices per m^2 overlain by the top 20% most deprived areas in LCRCA.

property value. The 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.

Table 5.10 Results from economic evidence module for study sites.

	Contamination Remediation Costs					
	Scenario 1 - Residential		Scenario 2 - Commercial/Employment		Scenario 3 - Public Open Space	
	Lower Estimate	Upper Estimate	Lower Estimate	Upper Estimate	Lower Estimate	Upper Estimate
Min	£0.00	£4,397.00	£0.00	£3,802.00	£0.00	£3,505.00
Mean	£1,009,603.6	£2,473,951.78	£798,944.19	£1,907,629.65	£799,527.35	£1,835,712.27
Median	£150,125.00	£367,537.00	£118,747.00	£281,652.00	£118,747.00	£272,312.00
Max	£46,608,321.00	£114,386,322.00	£37,229,557.00	£89,719,984.00	£37,312,247.00	£85,874,763.00
	Geotechnical Remediation Cost					
	Lower Estimate			Upper Estimate		
Min	£0.00			£0.00		
Mean	£39,968.50			£49,064.94		
Median	£0.00			£0.00		
Max	£2,747,972.75			£3,365,826.75		
	Land Value Estimates					
	Residential		Office (Central Business Dist.)	Office (Out of Town)	Industrial	Agricultural
Min	£4,561.75		£3,398.45	£1,502.78	£1,276.87	£90.36
Mean	£2,967,142.87		£1,923,638.31	£855,432.92	£759,178.88	£51,183.24
Median	£340,956.00		£260,672.00	£115,291.80	£113,531.99	£3,931.18
Max	£118,273,044.22		£92,770,913.47	£41,022,976.19	£47,189,828.82	£2,466,741.05
	Estimated New Build Property Total Sale Price					
	Houses (40 units/ha)			Flats (150 units/ha)		
Min	£8,625.92			£8,632.77		
Mean	£15,458,702.01			£32,989,991.00		
Median	£2,769,48.00			£4,178,303.26		
Max	£208,849,546.93			£487,371,448.32		

5.3.5 St Helens Local Plan – housing and employment land

5.3.5.1 Land Use potential

A 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 potential or above (Table 5.8). This reinforces that these areas are potentially suitable for residential development and could enable the delivery of some ~6500 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 (Figure 5.9). 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.

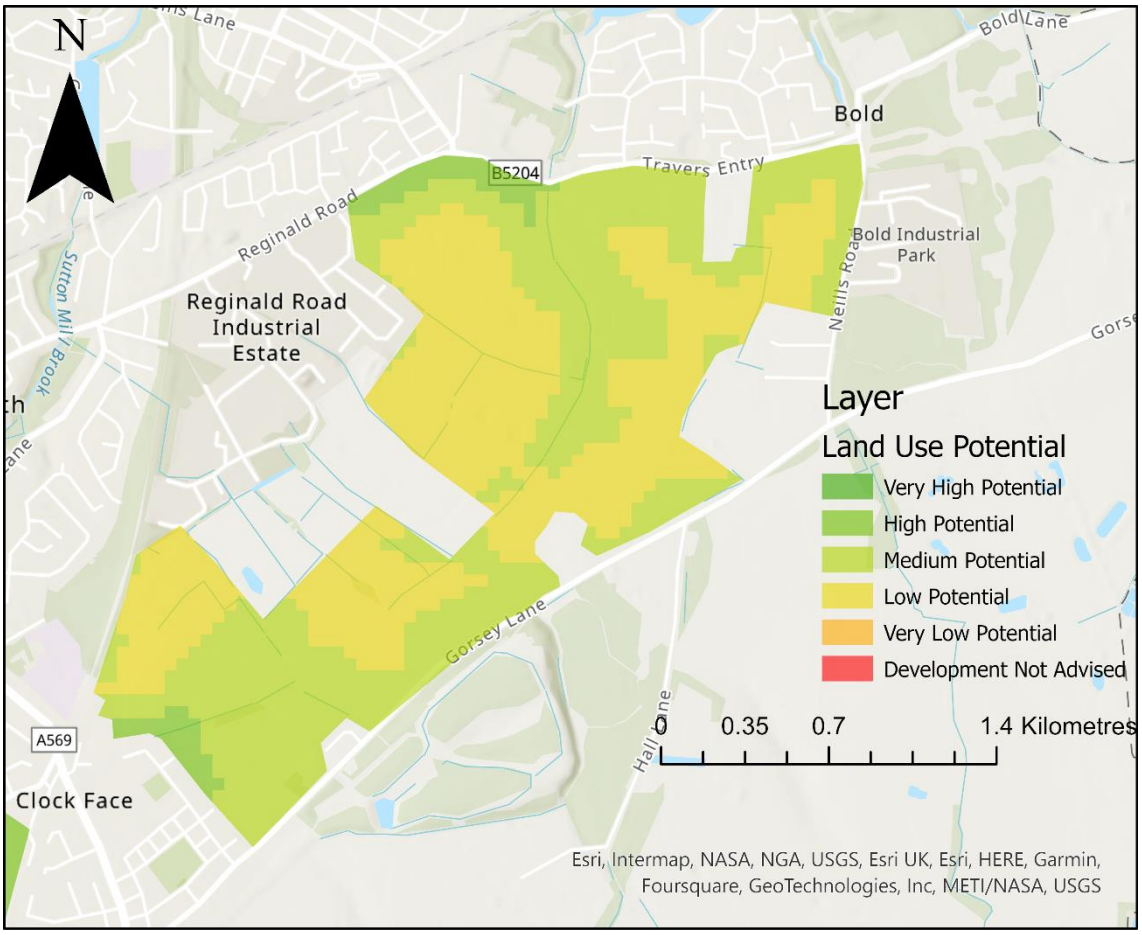


Figure 5.9 Residential land use potential assessment for St Helens Local Plan policy area 4HA**.**

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.

5.3.5.2 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 (Figure 5.10).

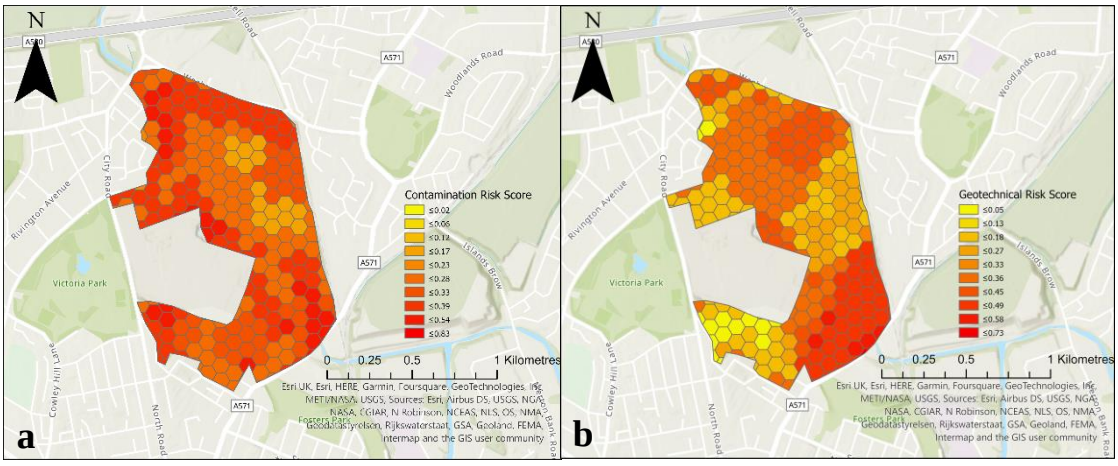


Figure 5.10 Ground risk scores for St Helens local plan housing development area 6HA, showing (a) contamination risk, and (b) geotechnical risk.

5.3.5.3 Economic Evidence

Results from the economic evidence module for the St Helens local plan for housing and employment land are surmised in Table 5.11. Because of 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, ~£75m and ~£1m respectively. Because of the large areas available for development, the estimated total sale price for houses are 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 ~£25m. Estimated land value for local plan development areas also shows

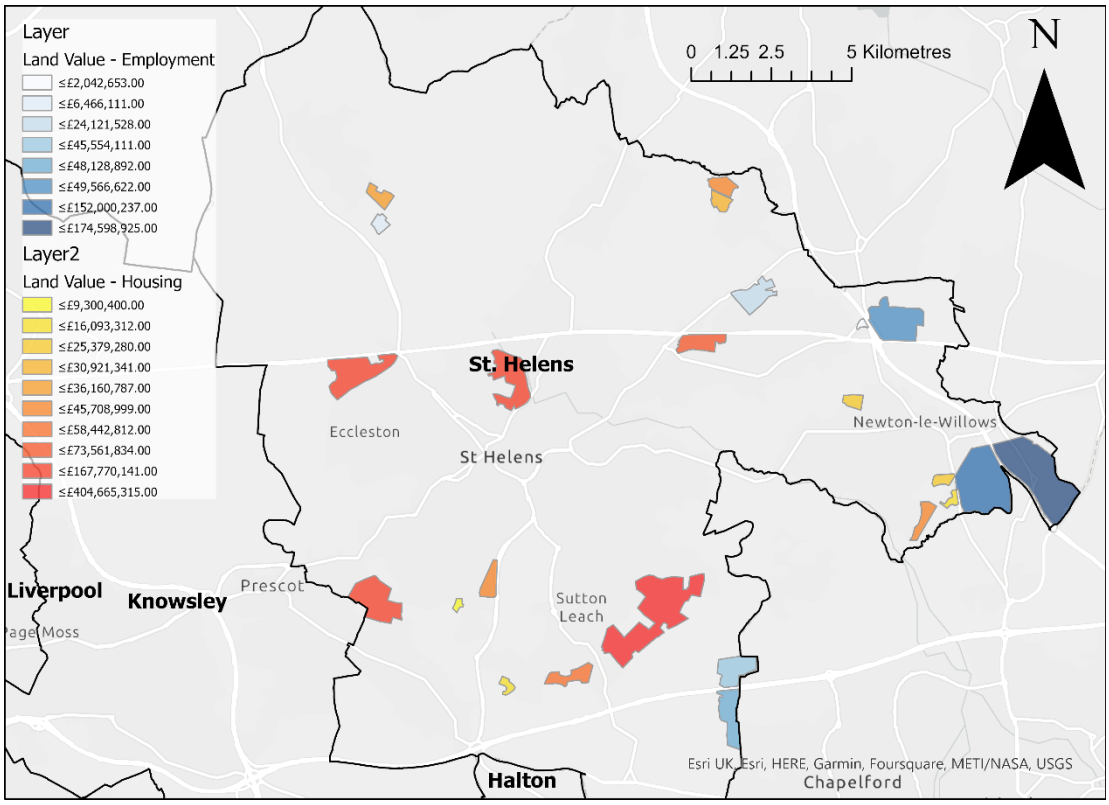


Figure 5.11 Estimated land value for each site within the St Helens local plan areas for housing and employment land.

high values (Figure 5.11), with the average residential land value for house areas as ~£80m, and the average land value for employment land as ~£62m.

Table 5.11 Results from economic evidence module for St Helens local plan development areas.

	Housing	Employment
Estimated Contamination Remediation cost*		
Min	£9,224,997.00	£4,590,482.00
Max	£323,949,760.00	£269,263,354.00
Median	£34,862,391.00	£63,542,743.85
Mean	£75,633,443.00	£96,990,426.00
Estimated Geotechnical Remediation cost		
Min	£29,742.00	£11,284.00
Max	£4,474,923.00	£3,373,597.00
Median	£631,015.00	£886,749.38
Mean	£997,113.00	£1,227,609.00
Estimated Land Value **		
Min	£9,300,488.00	£2,042,653.00
Max	£404,665,315.00	£174,598,925.00
Median	£40,654,934.00	£46,841,501.50
Mean	£80,070,963.00	£62,809,884.00
Estimated Total Property Sale Price (Houses)		
Min	£25,544,116.00	n/a
Max	£795,136,230.00	n/a
Median	£81,329,851.50	n/a
Mean	£140,538,045.00	n/a
* the estimated remediation costs for housing and employment local plan areas were calculated using residential and commercial scenarios respectively (Hammond et al., *2024).*		
** the estimated land values for housing and employment local plan areas were calculated for residential and industrial land value respectively (Hammond et al., *2024*)		

5.4 Discussion

5.4.1 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 5.3) 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 justify decisions made on the local plan and helps 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 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, because of underlying ground risk issues, significant economic support might be needed to remediate and develop these sites to *unlock* their economic potential. The outputs produced by the DSS 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.

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 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 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 and development of a DSS, including the MCDA and other data-driven factors affecting land use decision making, can be reliably applied to current worked examples. 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 mostly free publicly available, open source, datasets (Hammond et al. *2024*) (Chapter 4) provide scope for application to similar settings in the UK. 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 estimated figures 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, costs, 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 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.

5.4.2 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 the field (Hammond et al., 2021, 2023). The recent UK Levelling Up and Regeneration Bill, aims to improve the planning system by fully digitalising it and using digital tools to produce

spatial development strategies (DLUHC, 2022). 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. 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 enable UK planners and other public sector stakeholders to address 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, strategic planning, and enable the development of much-needed land resources. The use of digital tools, like this DSS, for assessment of land use planning options through the lens of sustainable development (social, environmental, and economic) and re-use of post-industrial land align with policies and initiatives, whereby land use planning stakeholders are encouraged to make use digital tools, GIS, and map-based assessments in their decision making processes.

Future policymaking 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 Digital, 2022), the majority of underlying data used to create the DSS is derived from open-source data (Hammond et al. 2024) (Chapter 4) 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 (such as the DSS presented in Hammond et al. (2024)), aligning with recommendations from the Geospatial Commissions *Finding Common Ground* report (DSIT and Geospatial Commission 2023); and (3) encourage the creation of innovative digital tools specifically for early-stage planning and assessment of brownfield land

(e.g., Hammond et al. 2024 (Chapter 4)). 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).

5.5 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 the application of the DSS. 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 verification demonstrates the development of effective digital tools to support brownfield redevelopment and should influence future policy development around approaches to creating such tools. The tool development-policy interaction will create a feedback loop where the effectiveness of digital tools and policies are mutually

enhanced within the brownfield redevelopment sector. The digital workflow used for the DSS is eminently 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 tool approach in helping guide the brownfield redevelopment planning process.

5.6 Author contributions

E. Hammond: Conceptualization, Methodology, Analysis, Investigation, Writing-Original Draft, Visualization, 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.

5.7 References

Albrechts, L., Barbanente, A., Monno, V., 2019. From stage-managed planning towards a more imaginative and inclusive strategic spatial planning. https://doi.org/10.1177/2399654419825655 37, 1489–1506. https://doi.org/10.1177/2399654419825655

Amato, F., Maimone, B.A., Martellozzo, F., Nolè, G., Murgante, B., 2016. The Effects of Urban Policies on the Development of Urban Areas. Sustainability 8. https://doi.org/10.3390/su8040297

Bartke, S., Schwarze, R., 2015. No perfect tools: Trade-offs of sustainability principles and user requirements in designing support tools for land-use decisions between greenfields and brownfields. J. Environ. Manage. 153, 11–24. https://doi.org/10.1016/j.jenvman.2015.01.040

Bennett, R., Bugri, J., Adade, D., Timo De Vries, W., 2023. Digital Twin for Active Stakeholder Participation in Land-Use Planning. L. 2023, Vol. 12, Page 538 12, 538. https://doi.org/10.3390/LAND12030538

Burinskiene, M., Bielinskas, V., Podviezko, A., Gurskiene, V., Maliene, V., 2017. Evaluating the significance of criteria contributing to decision making on brownfield land redevelopment strategies in urban areas. Sustain. 9, 759. https://doi.org/10.3390/su9050759

CPRE, 2022. State of brownfield report 2022 - [WWW Document]. URL https://www.cpre.org.uk/resources/state-of-brownfield-report-2022/ (accessed 4.26.23).

Crook, A.D.H. (Tony), Whitehead, C., 2019. Capturing development value, principles and practice: why is it so difficult? Town Plan. Rev. 90, 359–381. https://doi.org/10.3828/tpr.2019.25

Decoville, A., Feltgen, V., 2023. Clarifying the EU objective of no net land take: A necessity to avoid the cure being worse than the disease. Land use policy 131, 106722. https://doi.org/10.1016/J.LANDUSEPOL.2023.106722

Department for Levelling Up Housing and Communities, 2022a. Levelling Up and Regeneration Bill [WWW Document]. URL https://www.gov.uk/government/collections/levelling-up-and-regeneration-bill (accessed 2.17.23).

Department for Levelling Up Housing and Communities, 2022b. Digital planning reform - an overview [WWW Document]. URL https://dluhcdigital.blog.gov.uk/2022/06/28/digital-planning-reform-an-overview/ (accessed 2.18.23).

Department for Levelling Up Housing and Communities, 2022c. Levelling Up the United Kingdom . London.

Department for Levelling Up Housing and Communities, 2021. Plan-making [WWW Document]. URL https://www.gov.uk/guidance/plan-making (accessed 5.26.23).

Department for Science Innovation and Technology, Geospatial Commission, 2023. Finding common ground: Integrating data, science and innovation for better use of land

[WWW Document]. URL https://www.gov.uk/government/publications/finding-common-ground-integrating-data-science-and-innovation-for-better-use-of-land (accessed 5.24.23).

DLUHC Digital, 2022. Introducing the planning data platform [WWW Document]. URL https://dluhcdigital.blog.gov.uk/2022/09/28/introducing-the-planning-data-platform/ (accessed 6.17.23).

European Commission, 2023a. Urban Agenda for the EU [WWW Document]. URL https://commission.europa.eu/eu-regional-and-urban-development/topics/cities-and-urban-development/urban-agenda-eu_en (accessed 4.22.23).

European Commission, 2023b. Horizon Europe - Work Programme 2023-2024.

European Commission, 2022. Smart cities [WWW Document]. URL https://ec.europa.eu/info/es-regionu-ir-miestu-pletra/temos/miestai-ir-miestu-pletra/miestu-iniciatyvos/smart-cities_en (accessed 8.23.22).

European Commission, 2021. EU Soil Strategy for 2030 Reaping the benefits of healthy soils for people, food, nature and climate.

European Union, 2010. Report on the workshop on Re-using Brownfield Sites and Buildings.

Green, T.L., 2018. Evaluating predictors for brownfield redevelopment. Land use policy 73, 299–319. https://doi.org/10.1016/j.landusepol.2018.01.008

Groundsure, 2023. Groundscreen [WWW Document]. URL https://www.groundsure.com/products/groundscreen/ (accessed 5.24.23).

Guler, D., Charisoulis, G., Buttenfield, B.P., Yomralioglu, T., 2021. Suitability modeling and sensitivity analysis for biomass energy facilities in Turkey. Clean Technol. Environ. Policy 23, 2183–2199. https://doi.org/10.1007/s10098-021-02126-8

Hammond, E.B., Coulon, F., Hallett, S.H., Thomas, R., Hardy, D., Beriro, D.J., 2023. Digital tools for brownfield redevelopment: Stakeholder perspectives and opportunities. J. Environ. Manage. 325, 116393. https://doi.org/10.1016/J.JENVMAN.2022.116393

Hammond, E.B., Coulon, F., Hallett, S.H., Thomas, R., Hardy, D., Kingdon, A., Beriro,

D.J., 2021. A critical review of decision support systems for brownfield redevelopment. Sci. Total Environ. 785, 147132. https://doi.org/10.1016/j.scitotenv.2021.147132

Hammond, E.B., Coulon, F., Hallett, S.H., Thomas, R., Dick, A., Hardy, D., Dickens, M., Washbourn, E., Beriro, D.J., 2024. The development of a novel decision support system for regional land use planning for brownfield land. J. Environ. Manage. 349, 119466. https://doi.org/10.1016/J.JENVMAN.2023.119466

Hewitt, R., van Delden, H., Escobar, F., 2014. Participatory land use modelling, pathways to an integrated approach. Environ. Model. Softw. 52, 149–165. https://doi.org/10.1016/J.ENVSOFT.2013.10.019

HMLR, 2023. HM Land Registry Open Data [WWW Document]. URL https://landregistry.data.gov.uk/app/ppd/ (accessed 6.15.23).

Homes England, 2023. Homes England strategic plan 2023 to 2028 [WWW Document]. URL https://www.gov.uk/government/publications/homes-england-strategic-plan-2023-to-2028 (accessed 6.7.23).

Hou, D., Al-Tabbaa, A., O'Connor, D., Hu, Q., Zhu, Y.-G., Wang, L., Kirkwood, N., Ok, Y.S., Tsang, D.C.W., Bolan, N.S., Rinklebe, J., 2023. Sustainable remediation and redevelopment of brownfield sites. Nat. Rev. Earth Environ. 4, 271–286. https://doi.org/10.1038/s43017-023-00404-1

House of Lords, 2022. Land Use in England Committee report: Making the most out of England's land.

Howard, G.S., Dailey, P.R., 1979. Response-shift bias: A source of contamination of self-report measures. J. Appl. Psychol. 64, 144–150. https://doi.org/10.1037/0021-9010.64.2.144

Hurlimann, A., Moosavi, S., Browne, G.R., 2021. Urban planning policy must do more to integrate climate change adaptation and mitigation actions. Land use policy 101, 105188. https://doi.org/10.1016/J.LANDUSEPOL.2020.105188

Jenks, M., Dempsey, N., 2006. Future forms and design for sustainable cities. Futur. Forms Des. Sustain. Cities 1–456. https://doi.org/10.4324/9780080455525/FUTURE-FORMS-DESIGN-SUSTAINABLE-CITIES-NICOLA-DEMPSEY-MIKE-JENKS

Kahila-Tani, M., Kytta, M., Geertman, S., 2019. Does mapping improve public participation? Exploring the pros and cons of using public participation GIS in urban planning practices. Landsc. Urban Plan. 186, 45–55. https://doi.org/10.1016/J.LANDURBPLAN.2019.02.019

Larsson, A., Fasth, T., Wärnhjelm, M., Ekenberg, L., Danielson, M., 2018. Policy analysis on the fly with an online multicriteria cardinal ranking tool. J. Multi-Criteria Decis. Anal. 25, 55–66. https://doi.org/10.1002/MCDA.1634

Liverpool City Region Combined Authority, 2023. Spatial Development Strategy [WWW Document]. URL https://www.liverpoolcityregion-ca.gov.uk/sds/ (accessed 1.11.23).

Liverpool City Region Combined Authority, 2020. Liverpool City Region Plan for Prosperity Evidence Base [WWW Document]. URL https://www.liverpoolcityregion-ca.gov.uk/wp-content/uploads/Plan-for-Prosperity-Full-Evidence-Base.pdf (accessed 6.16.23).

Local Government Association, 2023. One Public Estate: Brownfield Land Release Fund (BLRF2) Round 2 [WWW Document]. URL https://www.local.gov.uk/our-support/one-public-estate/one-public-estate-brownfield-land-release-fund-blrf2-round-2-january (accessed 3.21.23).

Macgregor, C.J., Bunting, M.J., Deutz, P., Bourn, N.A.D., Roy, D.B., Mayes, W.M., 2022. Brownfield sites promote biodiversity at a landscape scale. Sci. Total Environ. 804, 150162. https://doi.org/10.1016/J.SCITOTENV.2021.150162

Marcomini, A., Suter, G.W., Critto, A., 2009. Decision support systems for risk-based management of contaminated sites, Decision Support Systems for Risk-Based Management of Contaminated Sites. Springer US. https://doi.org/10.1007/978-0-387-09722-0

Ministry of Housing Communities & Local Government, 2020a. Land value estimates for policy appraisal 2019 [WWW Document]. URL https://www.gov.uk/government/publications/land-value-estimates-for-policy-appraisal-2019 (accessed 6.15.23).

Ministry of Housing Communities & Local Government, 2020b. Planning for the Future. London.

Ministry of Housing Communities & Local Government, 2019. English indices of deprivation 2019 [WWW Document]. URL https://www.gov.uk/government/statistics/english-indices-of-deprivation-2019 (accessed 6.16.23).

Ministry of Housing Communities and Local Government, 2021. National Planning Policy Framework.

Ministry of Housing Communities and Local Government, 2017. Brownfield registers and permission in principle: frequently asked questions [WWW Document]. URL https://www.gov.uk/government/publications/brownfield-registers-and-permission-in-principle/brownfield-registers-and-permission-in-principle-frequently-asked-questions (accessed 2.5.20).

Nirandjan, S., Koks, E.E., Ward, P.J., Aerts, J.C.J.H., 2022. A spatially-explicit harmonized global dataset of critical infrastructure. Sci. Data 2022 91 9, 1–13. https://doi.org/10.1038/s41597-022-01218-4

Otsuka, N., Abe, H., Isehara, Y., Miyagawa, T., 2021. The potential use of green infrastructure in the regeneration of brownfield sites: three case studies from Japan's Osaka Bay Area. https://doi.org/10.1080/13549839.2021.1983791 26, 1346–1363. https://doi.org/10.1080/13549839.2021.1983791

Pelzer, P., 2017. Usefulness of planning support systems: A conceptual framework and an empirical illustration. Transp. Res. Part A Policy Pract. 104, 84–95. https://doi.org/10.1016/J.TRA.2016.06.019

Pettit, C., Bakelmun, A., Lieske, S.N., Glackin, S., Hargroves, K. 'Charlie,' Thomson, G., Shearer, H., Dia, H., Newman, P., 2018. Planning support systems for smart cities. City, Cult. Soc. 12, 13–24. https://doi.org/10.1016/J.CCS.2017.10.002

Pytel, S., Sitek, S., Chmielewska, M., Zuzańska-Żyśko, E., Runge, A., Markiewicz-Patkowska, J., 2021. Transformation Directions of Brownfields: The Case of the Górnośląsko-Zagłębiowska Metropolis. Sustain. 2021, Vol. 13, Page 2075 13, 2075.

https://doi.org/10.3390/SU13042075

Ren, Y., Lü, Y., Comber, A., Fu, B., Harris, P., Wu, L., 2019. Spatially explicit simulation of land use/land cover changes: Current coverage and future prospects. Earth-Science Rev. 190, 398–415. https://doi.org/10.1016/J.EARSCIREV.2019.01.001

Ridgway, J., Bee, E., Breward, N., Cave, M., Chenery, S., Gowing, C., Harrison, I., Hodgkinson, E., Humphreys, B., Ingham, M., others, 2012. The Mersey estuary: sediment geochemistry. British Geological Survey.

Russo, P., 2017. Usability of Planning Support Systems: analysing adoption and use in planning practice. The University of Melbourne.

Shao, Z., Sumari, N.S., Portnov, A., Ujoh, F., Musakwa, W., Mandela, P.J., 2021. Urban sprawl and its impact on sustainable urban development: a combination of remote sensing and social media data. Geo-spatial Inf. Sci. 24, 241–255. https://doi.org/10.1080/10095020.2020.1787800

Simonofski, A., Vallé, T., Serral, E., Wautelet, Y., 2021. Investigating context factors in citizen participation strategies: A comparative analysis of Swedish and Belgian smart cities. Int. J. Inf. Manage. 56, 102011. https://doi.org/10.1016/J.IJINFOMGT.2019.09.007

St Helens Borough Council, 2022. St Helens Borough Local Plan [WWW Document]. URL https://www.sthelens.gov.uk/article/3783/St-Helens-Borough-Local-Plan (accessed 5.24.23).

Stratigea, A., Papadopoulou, C.A., Panagiotopoulou, M., 2015. Tools and Technologies for Planning the Development of Smart Cities. J. Urban Technol. 22, 43–62. https://doi.org/10.1080/10630732.2015.1018725

The Land Trust, 2015. Brownfield as green space - The Land Trust [WWW Document]. URL https://thelandtrust.org.uk/who-we-are/policy/brownfield-green-space/?doing_wp_cron=1573832200.2426180839538574218750 (accessed 11.15.19).

Thomas, D., 2016. Placemaking: An urban design methodology, 1st ed, Placemaking: An Urban Design Methodology. Taylor and Francis. https://doi.org/10.4324/9781315648125/PLACEMAKING-DEREK-THOMAS

UK Government, 2022. UK's Digital Strategy [WWW Document]. URL https://www.gov.uk/government/publications/uks-digital-strategy (accessed 9.2.22).

UNEP, 2020. UNEP Enviornmental and Social Sustainability Framework (ESSF).

United Nations, 2023. THE 17 GOALS | Sustainable Development [WWW Document]. URL https://sdgs.un.org/goals (accessed 4.22.23).

Van Liedekerke, M., Prokop, G., Rabl-Berger, S., Kibblewhite, M., Louwagie, G., 2014. Progress in the Management of Contaminated Sites in Europe. https://doi.org/10.2788/4658

Wang, Z ;, Chen, X ;, Huang, N ;, Yang, Y ;, Wang, L ;, Wang, Y, Wang, Zihao, Chen, Xiaoqiang, Huang, Na, Yang, Yinan, Wang, Li, Wang, Yuan, 2022. Spatial Identification and Redevelopment Evaluation of Brownfields in the Perspective of Urban Complex Ecosystems: A Case of Wuhu City, China. Int. J. Environ. Res. Public Heal. 2022, Vol. 19, Page 478 19, 478. https://doi.org/10.3390/IJERPH19010478

World Bank, 2023. Urban Development Overview [WWW Document]. URL https://www.worldbank.org/en/topic/urbandevelopment/overview (accessed 6.7.23).

6 OVERALL DISCUSSION AND FUTURE RESEARCH RECOMMENDATIONS

6.1 Introduction

The focus of the PhD research has been on investigating the utilisation of digital tools in the brownfield land use planning redevelopment sector. The aim was to advance the development of GIS-based decision support systems (DSSs) that facilitate the sustainable reuse of brownfield land. To accomplish this aim, five distinct objectives were fulfilled (Figure 6.1). The first two objectives involved conducting a topic-specific critical review (Chapter 2) and engaging in sector-wide stakeholder consultation (Chapter 3). The purpose of these objectives was to analyse current trends and challenges pertaining to the field systematically. The insights gained from these objectives were essential in distilling the key information necessary for subsequent objectives which were the design, and development of the DSS that captures specific user requirements (Chapter 4) and the evaluation and verification of the DSS (Chapter 5). This chapter discusses the key findings and an overview of how the different research objectives have contributed to achieving the overall aim of the PhD research.

This PhD research makes a significant contribution to the existing body of knowledge, in relation to the scoping, development, and application of DSSs for brownfield redevelopment and environmental management. The critical review (Chapter 2) highlighted a notable deficiency in the availability of early-stage, regional-scale DSSs that incorporate socioeconomic factors comprehensively in assessing brownfield land for sustainable development. Further to this, the insights gained from sector-wide stakeholder engagement (Chapter 3) have shed light on specific challenges and opportunities for advancing digital tools for brownfield development (Sections 3.3.4 and 3.3.5). These

insights pertain to the benefits derived from integrating various software and informatics capabilities within a unified system, facilitating stakeholders' communication and decision making. The findings from the stakeholder consultation have broad applicability across environmental management (Section 3.3.5).

Through direct engagement with stakeholders in case studies, a user-led DSS was developed, applied, and verified – significantly contributing to the academic and applied literature on environmental management DSS. The PhD research has implications for the

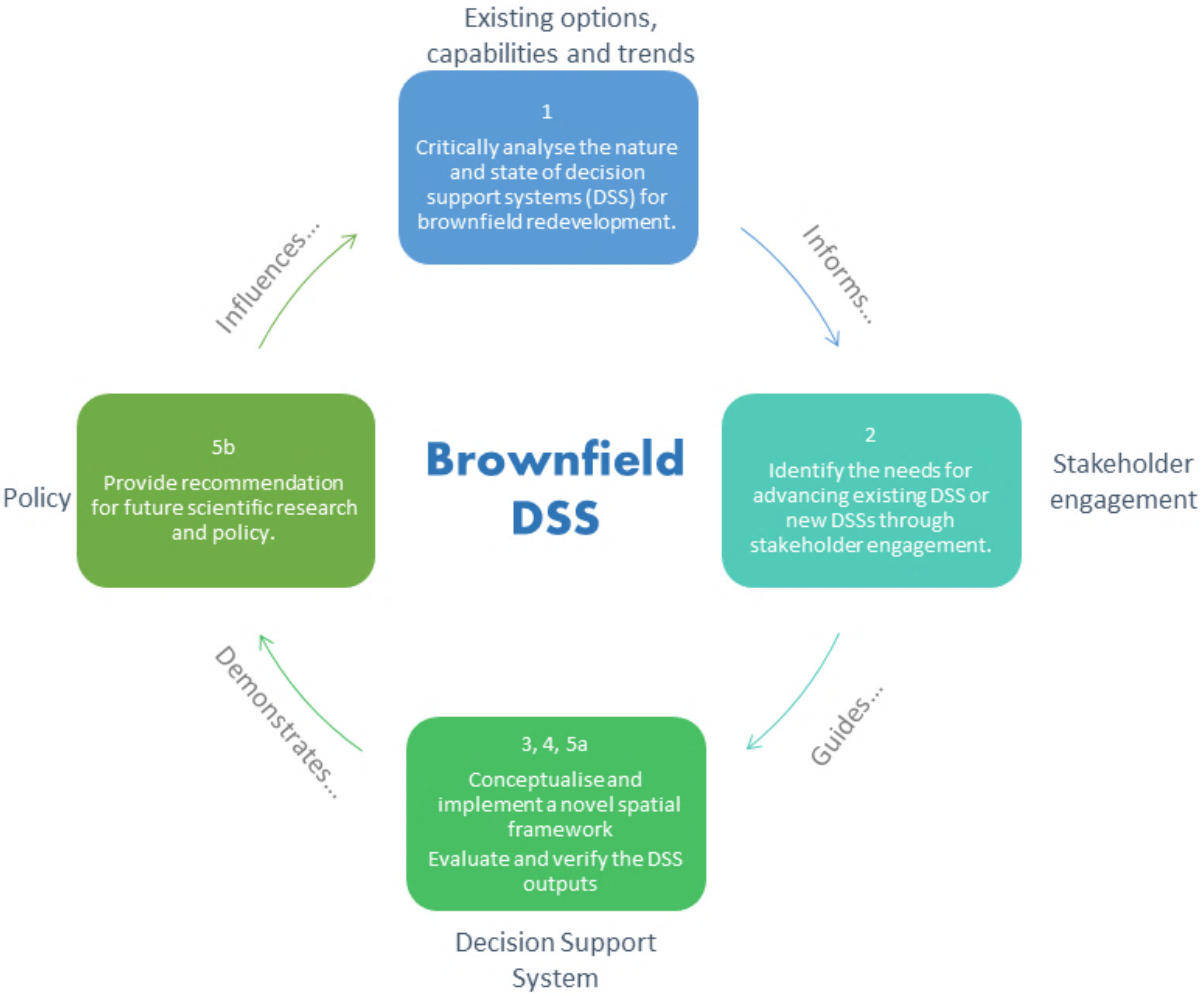


Figure 6.1 Schematic interrelations between the objectives (1 to 5) of the PhD research, and the overall impact on the brownfield sector. Objective 5 is split into two parts (a) verification, and (b) Recommendations for policy and future research.

direction of future policy on digital land use planning policy over national, regional, and local scales (Chapter 4, Chapter 5).

6.2 Key findings, implications, and knowledge gaps addressed

The integration of digital technologies is playing an increasingly central role in land use planning and brownfield redevelopment and revitalisation (Hammond et al., 2023a). Increasing our understanding of the advantages derived from using DSS across various scenarios can stimulate development and encourage decision makers to embrace these tools, ultimately fostering sustainable brownfield redevelopment.

Chapter 2 provides an in-depth analysis of the challenges encountered by current brownfield DSSs (Objective 1). The chapter highlights the complexities and limitations of existing DSSs and sheds light on the areas that require improvement and further investigation. The majority of existing DSSs for brownfield sites primarily focus on assisting in the selection of remediation technologies (Section 2.2.1) or evaluating the suitability of potential land uses (Section 2.2.2). There are fewer DSSs available for other applications and most of them concentrate on resolving late-stage or site-specific challenges. A comprehensive assessment also revealed opportunities for enhancing these approaches in the future. These enhancements encompass: (1) considering socio-economic factors alongside environmental factors, (2) expanding the scope of DSSs to address early-stage planning and redevelopment issues, which are currently insufficiently supported, (3) improving the user interface and experience of DSSs through enhanced stakeholder engagement and the adoption of modern web-based interfaces, and (4) integrating predictive modelling techniques to estimate risks and associated costs. The critical review (Hammond et al., 2021) (Chapter 2) has already started to have an effect on the academic and public sector literature. As of November 2023, the article has been

cited 33 times (40 times according to Google Scholar), by a range of papers across brownfield redevelopment, contaminated land, environmental management, and decision support system research. Additionally, the article (Hammond et al., 2021) (Chapter 2) was highly commended and cited in the World Health Organization's 2021 report, *Protecting health through urban redevelopment of contaminated sites* (WHO 2021).

Chapter 3 (Hammond et al., 2023a) presents the findings of a large-scale stakeholder consultation within the UK brownfield sector. A combination of findings from 5 interviews and 150 online questionnaire responses were used to investigate two areas, these being: (1) the level of digitalisation skills inherent in brownfield professionals, as well as, the strengths and limitations of existing digital tools, and (2) the importance in eliciting key brownfield redevelopment issues across different stakeholder groups. The results revealed significant disparities in the levels of digitalisation among different stakeholder groups. Analysis of the questionnaire responses indicated that digital tools have the potential to enhance data management and visualisation, and communication between experts and non-experts (Objective 2). However, for future digital tools to be effective, they must be user-friendly and interoperable with existing workflows.

Stakeholders identified several common challenges including: (1) the need for improved support in early-stage land use planning, (2) better understanding and communication of ground conditions and (3) enhanced knowledge and data collection for brownfield redevelopment economics (Objective 2). However, the relative importance of issues varies between stakeholders, with technical and non-technical stakeholders prioritising different aspects based on their roles. This UK sector-wide stakeholder consultation (Hammond et al., 2023a) (Chapter 3) is the first UK comprehensive study of its kind and

when combined with the critical review, it provides valuable evidence to inform the development of the DSS described in this PhD research (Objective 2).

Chapter 4 leverages the findings from the critical review and the stakeholder consultation, along with direct stakeholder engagement in case studies, to facilitate the development of a novel DSS (Objective 3). To achieve this, a robust use case was developed through semi-structured interview sessions held with three stakeholders from the Liverpool City Region (LCRCA): a strategic land use planner, a brownfield redevelopment officer, and a digital spatial planning officer. These interview sessions were used to formulate problem statements, user personas, and user stories (Section 4.2.1). Collectively these user requirements tools were used to inform the scope and design of the DSS (Objective 2, Objective 3), specifically, four areas that the DSS should address, including: (1) quantifying and comprehending ground risks associated with contamination and geotechnical hazards, (2) understanding economic viability and accessing data to support it, (3) facilitating sustainable place-making by assessing land use potential, and (4) developing an intuitive digital platform for visualising and interpreting DSS outputs. The findings from the use case development are aligned closely with those of the critical review and stakeholder consultation, reinforcing the pressing need for a DSS to address these areas.

Findings from stakeholder consultation (Section 3.3.5) and user requirements gathering (Section 4.2.1) highlighted the need for a digital web-based tool, easy to use, and spatial data-driven digital tools. This led to the development of a WebGIS-based DSS using ESRI's ArcGIS Experience Builder (ESRI, 2023). The DSS consists of three modules: land use potential, ground risk, and economic evidence, each of which was used in concert to address the challenge areas. A summary screen further displays top-level values/scores

from each module (Objective 3). The creation of DSS outputs involved utilising a custom Geographic Information System-Multi-Criteria Decision Analysis (GIS-MCDA) model, spatial analysis techniques, and a fuzzy-merge dataset matching approach (Objective 3). To ensure a user-centred approach, a series of stakeholder participation sessions and workshops were conducted, serving as a quality assurance stage in the development of the DSS. Specific user testing workshops were also conducted with 15 stakeholders from LCRCA (Objective 4). The results from the user testing workshops indicated that the DSS has a high degree of usability with most of the participants, who expressed enthusiasm for its potential to aid their decision making. Following user feedback, seventeen areas for improvement in the DSS were identified (Objective 4). Some of these improvements have already been implemented into the latest version of the prototype DSS, while the remaining improvements have been documented and *mocked up* for aiding future development work (Appendix 4.8.2).

Chapters 4 and 5 (Hammond et al., 2023b, 2024) show the practical implementation of the DSS, illustrating its versatility in facilitating investigations at various levels of resolution. The DSS enables assessments not only at the site-specific level but also across multiple brownfield sites within a region's post-industrial land (Sections 5.3.4 and 5.3.5). The DSS has the potential to impact the way decision-makers use digital tools during the early stages of the brownfield redevelopment process (before the construction phase) (Figure 6.2), enhancing their ability to make robust evidence-based decisions (Sections 4.3.1, 4.4, and 5.4). These applications include supporting evidence gathering, testing/validating spatial planning scenarios, sense-checking planning assumptions, and site identification/prioritisation, as noted in Hammond et al. (2024) (Chapter 4) (Objective 4). Hammond et al. (2024) (Chapter 4) emphasised the distinctive nature of

the DSS approach in terms of its comprehensiveness, methodologies, and the substantial involvement of users in its development, setting it apart from existing literature (Section 4.4).

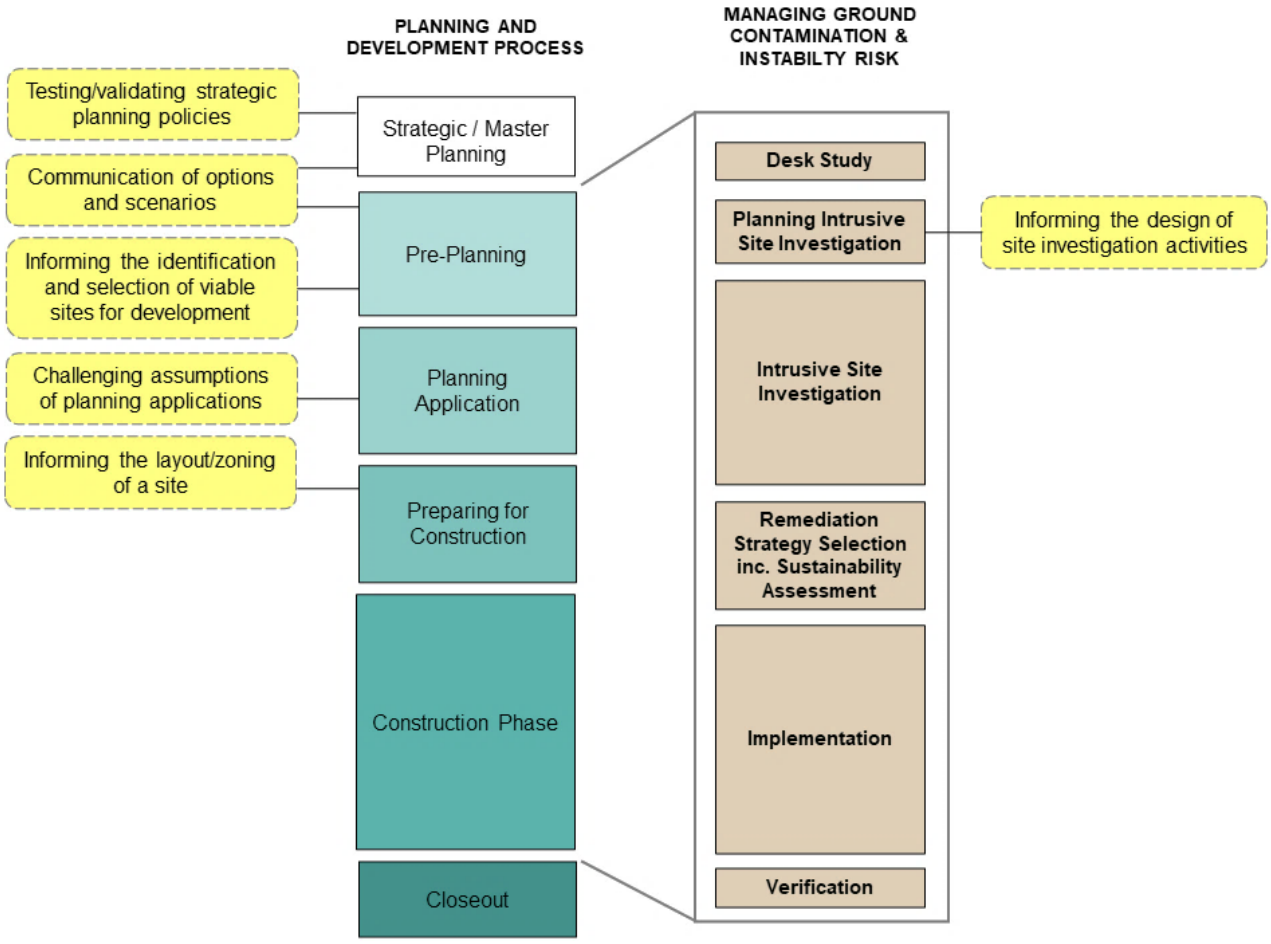


Figure 6.2 A simplified brownfield land development process, after Hammond et al (2021). Yellow boxes demonstrate how the DSS supports decision-makers in early-stage challenges.

Chapter 5 (Hammond et al., 2023b) presents the results of DSS verification and discusses the policy implications of the research (Objective 5). To verify the DSS, two methods were used. Firstly, qualitative verification of the DSS was carried out based on results from user testing (Objective 4). Secondly, quantitative verification was carried out on land-use potential models using a GIS-based comparison with real-world land use planning scenarios. During user testing, stakeholders involved expressed that the DSS outputs matched accurately with their understanding and expectations for each of the

eleven sites they investigated. The findings from the quantitative verification demonstrated an 80% to 100% match between land use potential models and the real-world planning scenarios they are designed to represent. When combined with results from user testing and case study evaluation, this further reinforces that the DSS results are accurate and suitable for use, addressing Objective 4, and in part, Objective 5.

Overall, this PhD research exemplifies modern, user led DSS development for brownfield applications. The methods and design of the DSS overcome several limitations observed in previous studies(see Section 2.3). To summarise; (1) a lack of DSS for early-stage regional-scale decision making, (2) a focus solely on the environmental dimension on of brownfield decisions, and (3) lack of user-led DSS development, hindering the usability of DSS interfaces and understanding by stakeholders. . The potential impact of the DSS on land use planning is substantiated by its successful implementation in multiple case studies, as well as the positive outcomes of user testing and verification (Chapter 5, Chapter 4). As outlined in Hammond et al. (2023b) (Chapter 5), the DSS was also applied to a genuine case study, where the outputs were used by LCRCA in early-2023 to support their assessment of 15 brownfield sites undergoing assessment for the allocation of Brownfield Land Release Funding (Round 2) (BLRF2) (Local Government Association, 2023). LCRCAs bid for this funding phase amounted to £2.9 m, and the DSS outputs played a supportive role in the process. The impact and influence the DSS outputs had on this process for LCRCA is highlighted by quotes below from stakeholders from LCRCA:

"The DSS has proven beneficial for bid and strategic project development to understand some of the potential early challenges that may arise for scheme viability and deliverability. Being able to estimate pre-existing challenges also allows us as an organisation to engage in key stakeholder discussions at an early stage to explore

routes to delivery. Centralised data on brownfield land will also help us to progress the development of funding pipelines, including future phases of BLRF2 in the future."

- One Public Estate and Land Commission Officer

"The DSS is particularly useful as a tested approach to brownfield land site evaluation. The NPPF (para 119) requires Local Planning Authorities to develop strategic policies that "make as much use as possible of previously developed or 'brownfield' land". Utilising the DSS will support Local Authorities and Combined Authorities in meeting this duty. The DSS was invaluable in supporting the LCR submission for BLRF2 funding. Utilising the DSS to evaluate the potential of the sites and developments being submitted for funding provided a further independent assessment to support the submission."

– Lead Officer, Spatial Planning

The use of the DSS to support early-stage planning and redevelopment of brownfield land is aligned with multiple current policies for sustainable development and the use of digital technologies in planning and land development (Objective 5). Specific research-policy links and implications have been discussed in detail in Chapter 5, however, key policies/initiatives relating to, and implicated by, this PhD research include: The UKs Levelling Up Strategy (DLUHC, 2022), Urban Agenda for the EU (European Commission, 2023), and the United Nations Sustainable Development Goals (United Nations, 2023). The creation of innovative digital tools, such as the DSS developed during this PhD research, will support decision makers in achieving goals set out by national policy and global initiatives for sustainable urban development, an area where brownfield redevelopment represents a crucial step.

6.3 Recent developments from literature and private/public sector

Since the publication of Chapter 1 (Hammond et al., 2021), there have been several developments, publications, and reports, not discussed within previous chapters that will be discussed here, in relation to the PhD research.

6.3.1 GIS-MCDA based methods

As discussed in Chapter 2 (Hammond et al., 2021), GIS/GIS-MCDA approaches are common within the field, allowing users of digital tools to assist in site selection for land-use planning. Since the publication of the critical review, five articles have been published utilising these methods.

Song et al. (2022) utilised a combination of population density data, existing land use data (including suspected contaminated land) and existing business development areas, to identify candidate brownfield sites in Changchun City, China. Once identified, brownfield sites were *confirmed* as vacant and available for development through ariel imagery and field survey. The approach allows for quick identification of prospective brownfield sites using GIS modelling, where there are no existing records.

Similarly, Adeoye and Okeleku (2022) also use a similar method to identify and evaluate the location suitability of existing landfill sites in Lagos. Using a combination of LANDSAT 7, and field GPS (Global Positioning System) surveys, landfill sites were digitised and then evaluated using GIS-MCDA AHP methodology to evaluate their suitability against five criteria: distance to water bodies, slope, distance to road, distance to a residential area, soil, and geology. Adeoye and Okeleku (2022) found that only 0.001% of the total land area of the study area was identified as highly suitable, 0.119% as moderately suitable and 99.4% as unsuitable for landfill sites. Additionally, Bodhankar et al. (2022) use a GIS-based ordered weighted average (OWA) method to calculate the

optimum allocation for urban land uses in Navi Mumbai, India. Bodhankar et al. (2022) combined remote sensing data with other spatial data to identify existing land use, and then generate the optimal land use based on their model. The data they use consists of the following: Cadastral data (boundaries, survey, land possession data), contour survey, geomorphology, soil layer, road network, and village centres. Their methods demonstrate another useful example of site identification and characterisation. Their OWA model was able to generate a suitability classification for their study area aiding in future local land-use planning activities.

Wang et al. (2022) use a combination of GIS data, aerial imagery, and questionnaires to local experts to identify potential brownfield sites in Wuhu City, China, which were confirmed through field surveys, and soil sampling to confirm contamination. Once identified, brownfield sites were evaluated for redevelopment potential on four indicators: policy factors (plan land use, government influence), social factors (community support, not-in-my-back-yard effect), economic factors (pollution management, redevelopment benefits), and characteristics (location, land use compatibility, transport capacity). Using a Delpi-Fuzzy AHP method they evaluated 19 sites for five different land uses. Wang et al. (2022) found that their method broadly aligned with the local Wuhu urban development plan. Similarly, Chen and Yang (2022) present a regional assessment model that evaluates brownfield sites based on a series of UN sustainable development goals (SDGs) (United Nations, 2023), and a cost-benefit matrix based on socioeconomic open data. Chen and Yang (2022) apply this framework to the island of Taiwan, with specific sites where a cost-benefit assessment is carried out, enabling stakeholders within Taiwan to select selected on brownfield sites to remediate and redevelop based on the degree to which they will provide SDG gains, and provide a positive cost-benefit ratio.

Song et al. (2022), Wang et al. (2022), Bodhankar et al. (2022), and Adeoye and Okeleku (2022) each provides an example of how brownfield land can be identified using and evaluated to support local land use planning decisions. Their methods utilise aerial imagery analysis in combination with ground truthing either through in-person surveys or questionnaires with local people. This approach, or similar methods to identifying individual brownfield sites (i.e., use of aerial imagery and land cover classifications) could be integrated into the DSS presented in this PhD research. Users of the DSS could be presented with a set of potential brownfield sites, identified using this approach (Adeoye and Okeleke, 2022; Bodhankar et al., 2022; Song et al., 2022; Wang et al., 2022) during the site definition/upload process, early into the user journey of the DSS. The DSS outputs could then be produced for these sites as per standard DSS use. Doing this would support an increase in the function of the DSS to allow for exploratory identifying and assessing previously unidentified brownfield land within post-industrial land areas, including sites that perhaps have not been identified during local assessments. This would support land use planners within a city region looking to increase their portfolio of available brownfield land for development.

Wang et al. (2022) and Chen and Yang (2022) demonstrated the inclusion of socioeconomic dimensions within their GIS-MCDA and evaluation methods, these socioeconomic criteria are more focused on the assessment of how well a sites land use performs against socioeconomic and sustainability targets and is aligned with recommendations of Hammond et al (2021) (Chapter 2) calling for greater inclusion of socioeconomic criteria. The selected of criteria chosen in these studies (Chen and Yang, 2022; Wang et al. 2022) are different from that chosen in the DSS presented in this PhD research and are better suited for the comparison between sites where lots of data and

information is available and where the deliverability of a site is known, and the decision is between the most sustainable end use and socioeconomic gains of developing a certain site. This is different from the DSS presented in this PhD research which primarily focused on proximity-based spatial panning factors affecting the suitability/potential of brownfield land for different end uses, with the primary aim of supporting the assessment of deliverability at an early-stage portfolio scale of investigation.

Despite the strengths of recent work, there are still several limitations. First, the degree to which stakeholders are involved in the process of DSS development all recent work (Adeoye and Okeleke, 2022; Bodhankar et al., 2022; Chen and Yang, 2022; Song et al., 2022; Wang et al., 2022) remains limited, with engagement primarily happening in one phase during scoping/evidence gathering. As such the tools/interfaces produced do not demonstrate a user-led approach, whereby DSSs are developed, tested, and evaluated with the intended user base. Furthermore, the approach used by Chen and Yang (2022) uses late-stage, site-specific data (i.e., specific development/building design information, and soil properties) that may not always be available for every project, or different application areas outside of their case study, calling into question the wider applicability of the approach. The limitations identified here are consistent with the general limitations identified by Hammond et al. (2023a, 2021) (Chapter 2, Chapter 3).

6.3.2 Other GIS-based methods

Aside from GIS-MCDA-based assessments, other geospatial tools have recently been developed to aid in land use planning, including the use of remote sensing and machine learning methods. Liang et al. (2022) use remote sensing analysis to understand land use change for brownfield sites within Hong Kong's New territories between the years 2000 and 2020. They utilised LANDSAT 7 and LANDSAT 8 data sampled at 4-year intervals

over the time period and applied 6 spatial metric calculations to evaluate brownfield land use change in terms of scale, distribution, density, and shape. Their findings show a periodicity to brownfield growth, from expansion to settlement to contraction, with land use changing to match the contemporary land use policy of the local government. Similarly, Mohajeri et al. (2023) utilise the machine learning (ML) method *Random Forest* to evaluate the density of urban neighbourhoods within the Oxford-Cambridge Arc in the UK, utilising OpenStreetMap and Ordnance Survey mapping as input data.

Both approaches by Mohajeri et al. (2023) and Liang et al. (2022) demonstrate using remotely sensed data and advanced processing techniques to understand land use and land use change over time, helping to inform urban planners in making decisions and creating policies for development/redevelopment of brownfield sites. The approach of Mohajeri et al. (2023) aligns with the recommendations of Hammond et al. (2021), encouraging the use of machine learning methods to understand and assess urban brownfield land. This method could be applied to the DSS presented in this PhD research, by incorporating an ML assessment of urban density into the GIS-MCDA methodology for land use potential assessments. The inclusion of these criteria would need to be discussed with land use planning stakeholders to identify its relevance for different end uses and influence over land use decisions, as per methods described in Chapter 4 (Hammond et al., 2024).

6.3.3 Non-GIS-based brownfield decision-support research.

Research has also been published aiming to establish new frameworks for the assessment of brownfield sites. Drenning et al. (2022) present a risk management framework to evaluate Gentle Remediation Options (GRO) for contaminated and brownfield sites. They develop this framework by applying GRO theory to existing risk management in Sweden and assess 3 scenarios against 13 specific contaminants that are commonly found in urban

brownfields. Drenning et al. (2022) then demonstrate the framework with a case study application on two sites in Sweden. Their findings show that the framework may itself be used as an early-stage decision-support tool to educate and engage stakeholders to identify relevant GRO. Similarly, Alsheri et al. (2023) also present a novel assessment framework for demonstrating the benefits of nature-based solutions (NBS) for brownfield redevelopment. Alsheri et al. (2023) modify an existing NBS framework by introducing ecosystem services and life cycle assessment dimensions. They demonstrate the framework on Queen Elizabeth Park in East London, and findings from their case study demonstrate the potential of the framework to support decision makers considering NBS remediation for brownfield sites.

Both studies (Alshehri et al., 2023; Drenning et al., 2022) are examples of non software-based DSS approaches, whereby a series of evaluation steps are employed to aid in decision making, ultimately encouraging sustainable redevelopment of brownfield sites. The scope of both studies is designed to support late-stage decision making, during the remediation stage of site development. The DSS presented in this PhD research could take findings from these studies, and incorporate assessments into a new module, whereby gentle remediation options and NBS solutions for sites assessed in the DSS are considered. This would likely be a highly interactive module, where users are required to input large amounts of the necessary information for a specific site selected using the DSS and allowing the GRO/NBS assessments to run. This addition would allow decision makers to begin to plan for sustainable remediation strategies for sites and assess the suitability of sustainable remediation options against existing information presented by the ground risk and economic evidence module (specifically, estimated remediation costs, which are calculated for *hard* remediation solutions). This potential addition to the DSS

further demonstrates the strength of the modular approach (discussed in Chapter 4). Once new methods, approaches, and capabilities for the assessment of brownfield land are available, they can be potentially incorporated into the DSS alongside existing capabilities.

6.3.4 Brownfield stakeholder engagement research

In addition to specific Decision support systems, tools, techniques, and frameworks developed, there has also been research to further understand the needs of stakeholders within brownfield redevelopment, in addition to the publication of Hammond et al. (2023a) (Chapter 3). Cui and Wenbo (2023) presented mapped results of stakeholder surveys and interviews to analyse local stakeholder attitudes toward the redevelopment of a large brownfield site in Jingang, China. Their mapping highlights where stakeholders believe different areas within the site should be utilised for different end-uses. They achieve this by having stakeholders place *brownfield landscape values* on different areas of the site, these values include; Historical value, Cultural value, Artistic value, Social value, Environmental value, and Leisure value. Similarly, Chowdhury et al. (2023) propose a methodology for mapping stakeholder perceptions towards the reuse of brownfield land as urban greenspace. They demonstrate the methodology on a site in Gothenburg, Sweden where mixed-use residential/greenspace development is being planned. Both studies (Chowdhury et al., 2023; Cui and Fang, 2023) show the benefits of using a map-based approach to understanding local attitudes towards the redevelopment of brownfield sites and understanding these preferences.

Future brownfield DSS research involving stakeholder campaigns should consider adopting a map-based approach alongside any other analysis. Doing so may help to increase their understanding of specific challenges within a region/area, and mapped

findings, could help to facilitate further discussion around the scope and design of DSS. For example, in this PhD research, adopting a map-based approach to conducting stakeholder engagement/consultation, could allow for a more detailed survey of local stakeholders within the Liverpool city region (using the scope of Chapters 3 and 4). Findings from this mapping process could enable the creation and design of sub-regional LPA-scale specific models and outputs and MCDA criteria. For example, stakeholders within Sefton might value proximity to road transport links for residential developments higher than stakeholders in Liverpool city-centre, where stakeholders might value proximity to greenspace higher than other areas. Using a map-based approach to understanding local stakeholder preferences would enable additional refinement of the DSS and improve the scalability of the methods.

Okeyinke et al. (2023) present findings from a stakeholder survey with 11 brownfield redevelopment stakeholders in the UK. Their investigation sought to identify key factors that land developers consider when redeveloping brownfield land. The methodology employed in their study is similar to that used in Hammond et al. (2023) (Chapter 3) albeit with a slightly different scope of investigation. However, their (Okeyinke et al. 2023) findings are consistent with findings from Hammond et al. (2023a) (Chapter 3) section with key criteria for brownfield redevelopment being around costs, contamination/hazards, and infrastructure/connectivity of a site. Okeyinke et al. (2023) use their index to create the BRIC (Brownfield Research and Innovation Centre) index. The BRIC index is a GIS-based site-selection tool that helps land developers filter sites from a database of sites they are looking to purchase, that meet the criteria highlighted from their survey. The approach by Okeyinke et al. (2023) further demonstrates (in addition to the PhD research presented in this thesis) the benefits of conducting

stakeholder consultation before digital tool development to ensure the scope and underlying methodology are reflective of the needs and preferences of stakeholders.

6.3.5 Public/private sector developments

Within the UK public sector, initiatives have been developed to investigate and support the adoption of digital technologies and increase digitalisation and digital innovation within public sector land use planning decision making. The Finding Common Ground report (DSIT and Geospatial Commission 2023) sets out findings from the Geospatial Commission's National Land Data Programme (NLDP), designed to help understand and influence land use decision making using spatial data and models (Cabinet Office and Geospatial Commission, 2022). Key findings and recommendations include, (1) changes to national policy decisions regarding digital land use tools, (2) promote the development of innovative tools across the private/public sectors, (3) strengthening links between, academic, industry, and public sectors, and (4) to develop data standards taxonomy for land use and analysis. As discussed in Chapter 5, the PhD research presented in this thesis aligns with these recommendations and can be used as an example of a collaborative piece of academic research to support sustainable brownfield land reuse.

One example of a new tool from the private sector (highlighted in the Geospatial Commissions report (DSIT and Geospatial Commission, 2023)) is Addland. Addland is a platform integrating mapping and datasets (Addland, 2023) supporting individuals, developers, land agents, and others looking to purchase land. Addland presents various map styles to identify land parcels and view critical data, including precise boundary calculations. The platform combines over 40 data layers from Ordnance Survey, HM Land Registry, and the Environment Agency, covering land classification, planning history, ownership, valuation, and constraints. This enables users of Addland to view a

wide range of datasets alongside each other to support their land purchase decisions. Similarly, to the DSS presented in this research, Addland presents a curated collection of datasets to be visualised concerning an area of interest. However, the scope of Addland is quite different. The DSS presented in this PhD research, provides results from research-based assessments specifically for brownfield sites to assess their development potential, likely ground risk, and likely economic values for the sites. Addland lacks the stakeholder-led decision analysis that increases the added value to the datasets to produce specific support for brownfield decision making.

Additionally, The Department for Levelling Up, Housing, and Communities' (DLUHC) Digital Land Team (DLUHC 2022; DLUHC 2022b), also champion the development of digital tools for land use planning and development. For example, DLUHC has recently launched round 1 of the PropTech Innovation Fund which funded 13 LPAs to work with 8 Property Technology (PropTech) companies to use innovative digital tools to make the planning process more open, accessible, and engaging for the public (DLUHC, 2023). One example from this scheme is the collaboration between Bolsover District Council, and the company, *The Future Fox.* Together they have developed 'PlaceBuilder' (The Future Fox, 2023), an interactive web-based tool that gamifies the planning process for a general audience. PlaceBuilder allows citizens to make land use choices, similar to planning officers and developers. Citizens can create and submit their own planning proposals by placing land use tiles on a potential development site. They can see real-time cost impacts and balance their budget between income-generating land uses and local infrastructure expenditures. This encourages engagement from demographics often least likely to participate in traditional planning events or consultations. PlaceBuilder aims to increase public engagement in land use choices and help communities better

understand and feel involved in development proposals that impact their area. PlaceBuilder demonstrates the benefits of creating interactive and engaging tools for public participation in understanding and contributing to the planning process.

Whilst a public engagement tool was outside of the original use case of the PhD research in this thesis, future work should be conducted to evaluate the effectiveness of the DSS in communicating its outputs, and implications for post-industrial land development in the application area (LCRCA) to the public. This could take the form of additional user testing workshops (akin to that presented in Chapter 4) with the public, or local community groups within LPAs. This may lead to further improvements or adaptations of the current DSS user interface, or the creation of a secondary DSS interface, to suit the needs of the public allowing them to understand and engage with the DSS outputs and assessments.

6.4 Further research recommendations

The development and application of future DSS research to support brownfield redevelopment would be influenced by several factors, including policy direction, regulations, recent developments from literature and the public/private sector, stakeholder attitudes, and technological capabilities. Future work should therefore focus on:

- Participation with industry-leading private-sector organisations to uncover developments/techniques/specific tools not currently within the published literature and investigate where developments from the academic literature can be developed using practices from the private sector.
- Conducting additional stakeholder engagement over a multi-national scale to gauge global brownfield sector attitudes towards digital tools and challenges within brownfield redevelopment. As discussed in Section 6.3.4, incorporating a

map-based approach to visualising findings from this would support large-scale engagement work. Doing this would not only allow for temporal and geographic comparison of important issues but would also provide evidence for the development of DSSs for different countries.

- An investigation of artificial intelligence/machine learning techniques for data exploitation, which should be investigated for supporting early-stage estimation/prediction of risks, site suitability, and economics. For example, one area where this could be especially impactful is in the use of predictive models to estimate remediation or ground engineering costs for a given site, this is supported by the findings of the critical review and the sector-wide stakeholder engagement.
- Developing the findings of this PhD research (Chapter 4) to a national scale DSS, embedding a design thinking approach into the development, to encourage a participatory approach to its creation. This will involve engaging with national government stakeholders/policy makers to produce additional case studies for different areas nationally/internationally to demonstrate the wider applicability of the DSS. This will also involve adjusting aspects of DSS input variables, such as the specific land use potential criteria use.
- Investigate the applicability and use of the DSS as a tool for public engagement in the planning process (discussed in Section 6.3.5)
- Further collaborative research should be conducted across several related disciplines (i.e., energy supply appraisal, remediation) to investigate the addition of new modules to the DSS (discussed in Sections 4.4 and 6.3.3).
- Exploring and encouraging the establishment of specific policies related to the development and use of digital tools for brownfield redevelopment applications.

6.5 Limitations of the research

It is recognised that there are several limitations to this PhD research, including:

- Limitations of the critical review (Chapter 2) of brownfield DSS are discussed in Section 2.4 and summarised here: (1) the subjective inclusion of articles over others during relevance filtering, (2) findings are based on data that was primarily collected from academic journals recorded in the Scopus database, (3) the geographical representativeness of the research reviewed is very Eurocentric, and (4) the time period considered was 23 years from 1998 to 2021.
- The principal evidence-gathering method for sector-wide stakeholder consultation (Chapter 3) was the use of an online questionnaire. This approach can be susceptible to sampling and participant access issues (Andrade, 2020; Wright, 2005). As the questionnaire required participants to voluntarily self-report responses, the sample of recorded answers may be subject to bias. Responses gathered may over-represent one particular group of brownfield stakeholders who were particularly motivated to respond to the questionnaire. For example, stakeholders driven by a desire to report negative experiences with digital tools, are a common motivation for responding to surveys and questionnaires (Andrade, 2020; De Leeuw, 2005). Additionally, the online questionnaire was only completed by stakeholders who are IT literate and who have access to the internet, and/or who had the opportunity to respond within the time period set. This demonstrates the susceptibility of the online questionnaire to sample and access bias. The questionnaire was designed to elicit specific views from UK brownfield stakeholders, and it is recognised that the applicability of the findings to other countries may be inappropriate, however, there is considered to be a significant overlap in the practice of brownfield land management across western countries

(Perez and Sanchez, 2017) to permit the projection of findings, discussed in Section 3.3.5.

- The wider applicability of the DSS and other limitations are discussed in Section 5.4.1. In summary: (1) the spatial data used in the tool need to be maintained and updated, (2) the criteria selection and weightings applied in the MCDA model were created together with case-study stakeholders from Liverpool City Region Combined Authority (LCRCA) and as such are subject to potential bias and assumptions, (3) during user-testing based verification of the DSS, users self-reported feedback and as such could have been subject to interview bias or response-shift bias.
- The prototype DSS presented in Chapter 4 possessed several technical limitations. The DSS and user interface were developed by the author, having initially had only limited experience/expertise in software application development. Creating a fully deployable future application of the DSS would need to draw on a team of experts in each of the different aspects of back-end/front-end including graphic design. The prototyping achieved in this PhD research was to illustrate the workflow process and what could be achieved.. Overall, Experience Builder was considered ideal for this stage of prototyping, allowing for all components and designs of DSS to be created and reconfigured efficiently and easily for user testing and iterative development purposes.

6.6 References

Addland, 2023. Land for sale - Find your land today with Addland [WWW Document]. URL https://addland.com/ (accessed 6.13.23).

Adeoye, N.O., Okeleke, C.C., 2022. Geospatial Analysis of Lagos State Landfill Site Suitability and Multi-Criteria Spatial Decision Support System. J. Geospatial Sci.

Technol. 3, 36–56. https://doi.org/10.54222/AFRIGIST/JGST/V3I1.4

Alshehri, K., Harbottle, M., Sapsford, D., Beames, A., Cleall, P., 2023. Integration of ecosystem services and life cycle assessment allows improved accounting of sustainability benefits of nature-based solutions for brownfield redevelopment. J. Clean. Prod. 413.

Andrade, C., 2020. The Limitations of Online Surveys. Indian J. Psychol. Med. 42, 575–576. https://doi.org/10.1177/0253717620957496

Bodhankar, S., Gupta, K., Kumar, P., Srivastav, S.K., 2022. GIS-Based Multi-Objective Urban Land Allocation Approach for Optimal Allocation of Urban Land Uses. J. Indian Soc. Remote Sens. 50, 763–774. https://doi.org/10.1007/s12524-022-01492-0

Cabinet Office, Geospatial Commission, 2022. New geospatial data projects to shape the future of land use [WWW Document]. URL https://www.gov.uk/government/news/new-geospatial-data-projects-to-shape-the-future-of-land-use (accessed 2.19.23).

Cabinet Office, Geospatial Commission, 2021. Geospatial Commission launches pilots to improve how data about land is used in the UK [WWW Document]. URL https://www.gov.uk/government/news/geospatial-commission-launches-pilots-to-improve-how-data-about-land-is-used-in-the-uk (accessed 2.19.23).

CARTO, 2023. CARTO | Location Intelligence & GIS for Cloud Natives [WWW Document]. URL https://carto.com/ (accessed 2.7.23).

Chen, I.C., Yang, B.C., 2022. Developing decision model and sustainable mapping to screen the efficiency of brownfield redevelopment based on socioeconomic open data. Sustain. Environ. Res. 32, 1–19. https://doi.org/10.1186/S42834-022-00139-6/FIGURES/9

Chowdhury, S., Kain, J.H., Adelfio, M., Volchko, Y., Norrman, J., 2023. Transforming brownfields into urban greenspaces: A working process for stakeholder analysis. PLoS One 18, e0278747. https://doi.org/10.1371/JOURNAL.PONE.0278747

Cui, Y., Fang, W., 2023. Research on the Spatial Perception of Stakeholders in Brownfield Redevelopment Based on Value Compatibility Analysis. Appl. Sci. 2023, Vol. 13, Page 620 13, 620. https://doi.org/10.3390/APP13010620

De Leeuw, E., 2005. To Mix or Not to Mix Data Collection Modes in Surveys. J. Off. Stat. 21, 233–255.

Department for Levelling Up Housing & Communities, 2022. Levelling Up and Regeneration: further information .

Department for Levelling Up Housing and Communities, 2023. What we've learnt from the PropTech Innovation Fund round 1 digital citizen engagement pilots - DLUHC Digital [WWW Document]. URL https://dluhcdigital.blog.gov.uk/2023/04/03/what-we-learned-from-round-1-proptech-innovation-fund-digital-citizen-engagement-pilots/ (accessed 5.26.23).

Department for Levelling Up Housing and Communities, 2022a. Levelling Up the United Kingdom . London.

Department for Levelling Up Housing and Communities, 2022b. Levelling Up and Regeneration Bill [WWW Document]. URL https://www.gov.uk/government/collections/levelling-up-and-regeneration-bill (accessed 2.17.23).

Department for Science Innovation and Technology, Geospatial Commission, 2023. Finding common ground: Integrating data, science and innovation for better use of land [WWW Document]. URL https://www.gov.uk/government/publications/finding-common-ground-integrating-data-science-and-innovation-for-better-use-of-land (accessed 5.24.23).

Drenning, P., Chowdhury, S., Volchko, Y., Rosén, L., Andersson-Sköld, Y., Norrman, J., 2022. A risk management framework for Gentle Remediation Options (GRO). Sci. Total Environ. 802. https://doi.org/10.1016/j.scitotenv.2021.149880

ESRI, 2023. ArcGIS Experience Builder [WWW Document]. URL https://www.esri.com/en-us/arcgis/products/arcgis-experience-builder/overview (accessed 1.6.23).

European Commission, 2023. Urban Agenda for the EU [WWW Document]. URL https://commission.europa.eu/eu-regional-and-urban-development/topics/cities-and-urban-development/urban-agenda-eu_en (accessed 4.22.23).

Hammond, E.B., Coulon, F., Hallett, S.H., Thomas, R., Hardy, D., Kingdon, A., Beriro, D.J., 2021. A critical review of decision support systems for brownfield redevelopment. Sci. Total Environ. 785, 147132. https://doi.org/10.1016/j.scitotenv.2021.147132

Hammond, E.B., Coulon, F., Hallett, S.H., Thomas, R., Hardy, D., Beriro, D.J., 2023a. Digital tools for brownfield redevelopment: Stakeholder perspectives and opportunities. J. Environ. Manage. 325, 116393. https://doi.org/10.1016/J.JENVMAN.2022.116393

Hammond, E.B., Coulon, F., Hallett, S.H., Thomas, R., Dick, A., Hardy, D., Dickens, M., Washbourn, E., Beriro, D.J., 2023b. From data to decisions: Empowering brownfield redevelopment with a novel decision support system. J. Environ. Manage. 347, 119145. https://doi.org/10.1016/J.JENVMAN.2023.119145

Hammond, E.B., Coulon, F., Hallett, S.H., Thomas, R., Dick, A., Hardy, D., Dickens, M., Washbourn, E., Beriro, D.J., 2024. The development of a novel decision support system for regional land use planning for brownfield land. J. Environ. Manage. 349, 119466. https://doi.org/10.1016/J.JENVMAN.2023.119466

Leaflet, 2023. Leaflet - a JavaScript library for interactive maps [WWW Document]. URL https://leafletjs.com/ (accessed 2.7.23).

LIANG, J., CHEN, J., TONG, D., LI, X., 2022. Planning control over rural land transformation in Hong Kong: A remote sensing analysis of spatio-temporal land use change patterns. Land use policy 119, 106159. https://doi.org/10.1016/J.LANDUSEPOL.2022.106159

Local Government Association, 2023. One Public Estate: Brownfield Land Release Fund (BLRF2) Round 2 [WWW Document]. URL https://www.local.gov.uk/our-support/one-public-estate/one-public-estate-brownfield-land-release-fund-blrf2-round-2-january (accessed 3.21.23).

Mapbox inc., 2023. Mapbox [WWW Document]. URL https://www.mapbox.com/ (accessed 2.7.23).

Mohajeri, N., Walch, A., Smith, A., Gudmundsson, A., Assouline, D., Russell, T., Hall, J., 2023. A machine learning methodology to quantify the potential of urban densification in the Oxford-Cambridge Arc, United Kingdom. Sustain. Cities Soc. 92.

https://doi.org/10.1016/j.scs.2023.104451

Okeyinka, O.M., Khan, R., Pathirage, C., Mahammedi, C.E.D., West, A., 2023. A Critical Review of Developers' Decision Criteria for Brownfield Regeneration: Development of the BRIC Index. Sustain. 2023, Vol. 15, Page 7105 15, 7105. https://doi.org/10.3390/SU15097105

Pérez, A.P., Peláez Sánchez, S., 2017. European achievements in soil remediation and brownfield redevelopment. Joint Research Centre Report (European Commission). https://doi.org/10.2760/91268

Song, Y., Lyu, Y., Qian, S., Zhang, X., Lin, H., Wang, S., 2022. Identifying urban candidate brownfield sites using multi-source data: The case of Changchun City, China. Land use policy 117, 106084. https://doi.org/10.1016/J.LANDUSEPOL.2022.106084

The Future Fox, 2023. PlaceBuilder [WWW Document]. URL https://www.thefuturefox.com/placebuilder (accessed 6.13.23).

United Nations, 2023. THE 17 GOALS | Sustainable Development [WWW Document]. URL https://sdgs.un.org/goals (accessed 4.22.23).

Wang, Z ;, Chen, X ;, Huang, N ;, Yang, Y ;, Wang, L ;, Wang, Y, Wang, Zihao, Chen, Xiaoqiang, Huang, Na, Yang, Yinan, Wang, Li, Wang, Yuan, 2022. Spatial Identification and Redevelopment Evaluation of Brownfields in the Perspective of Urban Complex Ecosystems: A Case of Wuhu City, China. Int. J. Environ. Res. Public Heal. 2022, Vol. 19, Page 478 19, 478. https://doi.org/10.3390/IJERPH19010478

World Health Organization, 2021. Protecting health through urban redevelopment of contaminated sites: planning brief.

Wright, K.B., 2005. Researching internet-based populations: Advantages and disadvantages of online survey research, online questionnaire authoring software packages, and web survey services. J. Comput. Commun. 10. https://doi.org/10.1111/J.1083-6101.2005.TB00259.X/4614509