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Review

Free and open source urbanism: Software for urban planning practice

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ABSTRACT

Free and open source tools present numerous opportunities to support current urban planning practice. However, their overview is fragmented, and the uptake among planning professionals remains lacklustre. Recent discourse in the domain of planning support tools attribute poor take up to the lack of understanding on the landscape and functionality of available tools, and how tools can add value to the planning process. We provide an understanding of the state of the art concerning open source tools for urban planning from journal articles, software repositories, and social media. Our search documented 70 open source tools that support different stages of the urban planning process. We cover an additional set of 54 peripheral tools to support domains related to urban planning. In the process, we formalise and describe the urban planning process and find that the entire planning process can be conducted using open source software. Tools focusing on street networks and geographic spatial analysis are the mainstay of current implementation. Sixty percent of tools are only accessible through an application programming interface, while 43% rely on Python for development. The scenario planning, public participation, and evaluation phases of the planning process present many untapped opportunities for open source software development. Findings will help urban planners and researchers to employ these tools for professional practice, and assist software developers to identify opportunities for software development in urban research.

1. Introduction

Planning support tools are computational software that assist—not replace—urban planners to more effectively undertake their day-to-day professional tasks, understand urban complexity, and plan for more sustainable and resilient cities (Batty, 1995; Deal, Pan, Pallathucheril, & Fulton, 2017; Geertman & Stillwell, 2020; Klosterman, 1997; Pettit et al., 2018). The advent of dynamic and complex information streams of urban data has not only digitised planning profession but increased the intractability of common planning tasks such as urban modelling and participatory planning (Batty, 2021; Boland, Durrant, McHenry, McKay, & Wilson, 2021). In this new environment, urban analytical methods have become indispensable. A recent global survey on urban administrations by ESI (2021) found that close to 40% of cities rated timely access to data analytics as an imperative aspect of Covid-19 response. In addition, the 2021 Annual Global Risk Report by the World Economic Forum, stresses how urban risk factors are increasingly complex and jointly compounded by sweeping issues such as social fragmentation, environmental degradation, and global business shakeouts (WEF, 2021). In a time of rising fiscal austerity, data-driven and evidence-based decision making processes provide a solution for resource allocation (da Cruz, Rode, & McQuarrie, 2019; De Vries, Bekkers, & Tummers, 2016). Although rare, studies such as the one of Waheed et al. (2020) juxtapose traditional approaches of planning against those augmented by planning support tools and conclude that the latter provide significant time saving for comparable tasks.

Commercial software, despite its many limitations, remain the mainstay of contemporary urban planning practice (Fleischmann, Feliciotti, & Kerr, 2021; Tripathy, Rao, Balakrishnan, & Malladi, 2020). Following a decade of rapid development, the current landscape of open source software presents numerous opportunities to augment a wide range of urban analytical processes from modelling to visualisation, and is increasingly seen as a robust alternative to proprietary software (Boeing, 2017; Lindberg et al., 2018; Morley & Gulliver, 2018; Rossetto et al., 2018; Smith, 2016; Yang, Heppenstall, Turner, & Comber, 2019). Nonetheless, there remains a significant gap in uptake and application of planning support tool (Geertman, 2017; Harris, 1999; Klosterman, 1997). Overall, reasons for dismal adoption can be grouped into three

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main factors: (1) the complex and multidimensional nature of planning tasks makes it hard to design tools; (2) technicality and lack of user-oriented design; and (3) a lack of understanding on diversity, functionality and potential use cases, limit the application of tools.

Moreover, to the best of our knowledge, there has not been a review paper examining open source software related to urban planning. Throughout this paper, we make several efforts to address this concern. Our goal is to present an extensive overview of the emergent landscape of free and open source tools for urban planning to (1) promote adoption of free and open source tools in professional planning practice; and (2) explore software development opportunities for urban planning use cases. We first discuss the definition of free and open source software and implications of open source developments in various application domains of planning. Then we examine comparative reviews and discuss how our work builds upon and differs from related work by others. This part is followed by a discussion on the study's methodology which includes our selection (and exclusion) criteria for tools and an overview of our review approach. Subsequently, we present our compiled list of tools and accompany it with a finer-grained categorization of application to specific planning stages as defined in urban planning literature (Daniel, 2020; Yeh, 1999). Our analysis includes a thematic analysis of compiled tools and their use cases as identified from academic literature. We conclude the paper with a discussion on software development and research opportunities.

2. Free and open source urbanism

2.1. Background

For the purpose of our study, we adopt a similar definition of free and open source software by Steiniger and Hunter, Sreepathi, and DeCarolis (2013), referring to software where users can have the freedom to use, modify, adapt, redistribute, and have access to development source code. Under this definition, free and open source software is free-to-use in the sense that users can re-purpose, modify, and even sell the software, but is not guaranteed to be free-of-cost (although most do not require users to pay) (Aguilar, Calisto, Flacke, Akbar, & Pfeffer, 2021; Chmielewski, Samulowska, Lupa, Lee, & Zagajewski, 2018).

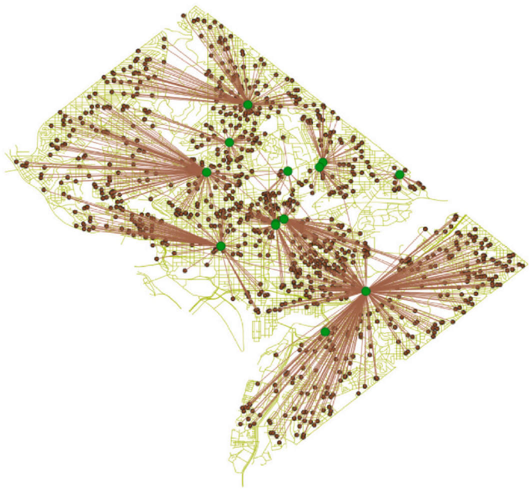
Free and open source projects have been one of the main contributors to the rapid rise of planning support tools in the last decade. At the heart of this modern transformation is a phenomenon of 'Platform Urbanism' where digital platforms have increasing influence over the design, governance, and disruption of cities (Barns, 2019; Batty, 2021). The idea has its early roots in the concept of 'Government as a Platform' which began as an initiative for software firms to co-design applications with government departments instead of procuring such services (Barns, 2016; O'Reilly, 2011). Since then, the idea was largely spurred by the rise of its user community and software developers. On one hand, software users today are no longer passive consumers of software, but also play an active part in popularizing (e.g. starring a repository), maintaining (raising issues on remotes), and influencing the direction of future developments (Sherratt, 2013). On the other hand, the rise of community developers indicates that open source software can also obtain more development support from community contributors (Kitchin, 2014; Mackenzie, 2019). In this sense, users are both producers and consumers of software, and are empowered through their direct autonomy over the distribution and management of said software. Just as important is the proliferation of open datasets which catalyses the growth of open source software. For example, open datasets in the built environment have helped to encourage reproducibility and benchmarking of analytical workflows (Miller et al., 2020; Miller & Meggers, 2017), and provide opportunities to explore new use cases (Biljecki, 2020; Miller et al., 2021).

A discussion on the development of open source software for urban planning would not be complete without mentioning contributions from geographic information science. Arguably, the maturity and subsequent application-driven unfolding of the latter laid much of the heavy groundwork for the former (Bivand, 2021). As summarised by Anselin (2012), the rise of open source geographic information science (GIS) tools can be attributed to three main factors: (1) pioneering of early open source geometric data handling libraries (e.g. GDAL, GEOS, etc.) and industry standards; (2) spatial indexing (allowing applications to tap into powerful back end functions, e.g. in-built relational query) of open source industry standard databases such as PostGIS; and (3) implementation of open architectures and well-documented APIs. Holistically, these factors helped to ease barriers to software development, and promote the accessibility and extensibility of the open source GIS ecosystem. For example, the QNEAT3 QGIS plug-in helps to extend geospatial network computation capabilities with optimised algorithms for origin-destination flows (see Fig. 1a). Geospatial analysis and mapping applications continue to feature as one of the predominant domains for open source urban planning tools.

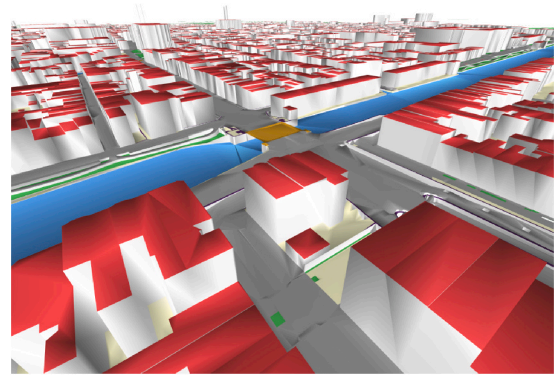
From the user's perspective, a switch from commercial to open source software entails several trade-offs. Among various concerns, Steiniger and Bocher (2009) underline software and license support as a foremost aspect that users should consider before making the switch to open source software. While acknowledging that open source software can offer more support for standards and commonly used file formats, their study notes that the level of support is highly dependent on maturity of said software and its user community. For example, mature packages such as OSMnx offer a well structured contribution guidelines page which allows users to submit their feedback, propose features, report bugs, and seek implementation help. Yet, structured guidelines currently remain exceptions rather than the norm among open source projects. In the case of business operations, additional socio-cultural and economic considerations can factor into software choice (Nagy, Yassin, & Bhattacherjee, 2010; Macredie & Mijinyawa, 2011; Li, Tan, Xu, & Teo, 2011; Qu, Yang, & Wang, 2011). For example, commercial vendors such as ESRI reportedly spend a significant proportion of their annual budget (around 30%) on research and marketing. For time-pressed practitioners, the optimised workflows and customised user interfaces could offer significant time savings on common tasks. Users also receive tailored updates on new software features without needing to pore through software documentation. The amount of resources that commercial companies put into user outreach and networking events (e.g. GIS user conferences) is also significant. In some cases, buying into commercial software could meet more than project needs and extend into branding or networking opportunities.

Recent discourse highlights the increasing popularity of open source projects for diverse urban applications and workflows—water resource management (Swain et al., 2015), geospatial applications (Steiniger & Hunter, 2013), pedestrian accessibility (Liu et al., 2021), low-carbon neighbourhoods (Zwickl-Bernhard & Auer, 2021), transportation modelling (Lovelace, 2021; Lovelace, Parkin, & Cohen, 2020), urban morphology (Biljecki & Chow, 2022; Fleischmann et al., 2021), 3D GIS (Ledoux et al., 2021; Liang, Gong, Zhou, Ibrahim, & Li, 2015), and urban water runoff (Rossetto et al., 2018). For example, 3dfier facilitates generation of 3D city models from 2D building footprints (see Fig. 1b). As noted by Rey (2009) and Pelzer (2015), proprietary software suffer from several planning-specific limitations which can be addressed by open source alternatives: (1) silos among government units is a key issue hindering effective urban planning and this is made worse by quotas on software installation which inhibit widespread adoption of common software; and (2) high software adoption cost and long end-to-end duration (development to implementation) makes the planning process less adaptable to dynamic change. The latter point is especially critical for planning practitioners operating in socio-political climates with volatile political will.

Fundamentally, the choice to focus on open source planning tools aims to reflect ongoing trends happening to planning practice. These trends point to an increasingly distributive, decentralised, and platform-oriented way (e.g. sharing economies) of conducting urban planning



(a) Network distance computation with QNEAT3 in District of Columbia, USA. Source: Open Data DC.



(b) Construction of 3D city models with 3dfier in Delft, Netherlands. Source: 3D Geoinformation Group, TU Delft.

Fig. 1. Examples of open source software that cater to urban planning processes.

that reflect how societies, economies, and cities are digitally embedded. As argued by Batty (2021): 'This is not simply a plea for planning to engage in using more digital tools, it is a plea for attempting to see how we can make sense of the way our societies through our focus on cities, are being automated'. In this vein, the proliferation of open source tools and use cases are indicative of broader trends in urban planning research.

2.2. Related Work

Our efforts build upon past review of open source software in other application domains (Table 2). Existing reviews focus on discussing technical aspects of software development, evolution of tools in certain application domains, and evaluating the efficacy of tools for general workflows. We identified three review papers that may be considered as related work.

In their review, Steiniger and Hunter et al. (2013) provide a functional typology of free and open source GIS software focused on operational characteristics. In the last decade, the emphasis on computing and the city has shifted from understanding software to a more application driven focus on software. This shift is largely driven by the advent of new forms of urban data which inspired novel urban analytical methods (Batty, 2019; Lazer & Radford, 2017; Singleton, Spielman, & Folch, 2017). Today, many methodological advancements are presented through open source initiatives, making open source a platform for users to participation in the frontier innovation. To reflect this change, our review predominantly explores the purpose and function of tools specific to urban planning application, use cases, and tasks.

The recent exploratory work by Fleischmann et al. (2021) focuses on open source software for urban morphology. They demonstrate that a programming/code based interface for geographic data science is fully replicable, reproducible, and expandable, allowing urban morphometric studies to be conducted entirely within a single environment. Our paper expand upon this analysis in two areas. First, as noted by Calafiore, Palmer, Comber, Arribas-Bel, and Singleton (2021); Birenboim, Helbich, and Kwan (2021), cities are complex entities that can only be understood through urban structures at different scales. Urban computational methods should thus demonstrate their application to various urban scales. To capture application across different urban scales, our review encompass application domains spanning from the macro (network analysis, urban mobility, urban morphology) to the micro (environmental modelling, energy modelling and simulation). Second, we relate developments in computational methods to the current state of urban planning. While digital transformation is accelerating software adoption, it is important to acknowledge that legacy systems are still well entrenched into traditional urban planning practice in many parts of the world. With this consideration in mind, we document essential support and access type information to assist contemporary urban planners in their adoption of open source technology. Through our review of software access types, we note that many software provide direct web-based access or custom graphic user interface (GUI) access without the need for users to code. However, we also note that majority of tools are only accessible to those with some programming knowledge. Our review reveals that almost all tools provide easily accessible information on installation, practice data sets, and tutorials to help users get started. This finding potentially suggests that urban planners and researchers need not become expert programmers to utilise these tools effectively.

Lastly, the review by Lovelace (2021) explores the current landscape of open source software and conclude that open source solutions can fulfill the professional needs of modern day transport planners. They argue that proprietary software limit the extent to which transportation planning can answer modern aspirations to become more transparent, accessible, and participatory. Concerns for better accountability and more collaborative planning extend beyond transportation planning and remains an active area of discussion throughout urban planning. Our review captures the evolving nature of urban planning and computational methods for understanding the city at large. We expand on the aforementioned review by documenting the wide range of application domain and use case provided by open source software for various stages of the planning process, not limited to, scenario planning and public participation which form essential stages for collaborative planning. The multi-disciplinary nature of software applications in urban planning is indicative of the complexities underlying urban systems.

3. Methodology

3.1. Screening, selection criteria, and information extraction

Software were screened for inclusion based on the following criteria: (1) software must connect to urban planning/studies related application or use cases; (2) tools do not have proprietary characteristics (i.e. plug-ins for proprietary software or those requiring paid API with limits); (3) spatial extent applies to urban planning scales of micro (neighbourhood), *meso* (precincts), and macro (city/metropolitan); (4) software should be targeted at end users. By definition, these criteria excluded popular but general packages for data visualisation (ggplot; plotly), data extraction (osmextract; osmdata; streetview; pygsvpano), and data pre-processing (pandas, numpy, scikit-learn), and data validation tools (val3dity). Importantly, we omit several essential 'building block' software such as PostGIS, GDAL, OGR, GeoTools, deegrees, Sextante, JTS Topology Suite, leaflet, etc. Not discounting the importance of the aforementioned tools in the urban analytics and planning workflow, our criteria reflect a consistent focus on tools relevant to urban planning application and use cases.

Our overall search returned a final list of 124 open source software tools. Most exclusions were those targeted for general purpose applications without explicit relevance to urban application domains. Other reasons for exclusion include the lack of a licence file which limited code reuse and redistribution and software being outdated.

Several key characteristics were then extracted for each of the selected tools: (1) use case focus; (2) developer type; (3) number of contributors; (4) number of stars on Github; (5) access type; (6) licensing; (7) primary development language; (8) operating system support; (9) reference citation; (10) installation instructions; (11) availability of example data sets; and (12) availability of vignettes/user tutorials.

3.2. Search process

A systematic review of free and open source software presents unique challenges: (1) there is no ready definition of what is considered a 'tool'; (2) open source software documentation and standards may be lacking or disorganised; (3) loose coupling between documentation and research output as software developers may not be researchers, vice versa; and (4) a tool may be open source but its environment might be proprietary (e.g. open source extensions for a commercial software).

To deal with these challenges, we adopted a state of the art literature search of past review articles via Scopus. A similar approach has been adopted by previous studies (Fleischmann et al., 2021; Lovelace, 2021; Palomino, Muellerklein, & Kelly, 2017; Pettit et al., 2018; Russo, Lanzilotti, Costabile, & Pettit, 2018; Steiniger & Hunter, 2013). To expand our search on potential tools, we also examined code repositories, relied on word of mouth recommendation, and social media feeds. The search was conducted from August 2021 until November 2021. Fig. 2 lays out the structure and methodology of the study.

First, code repositories (such as GitHub, GitLab, and GitBucket) have emerged as a popular way for software developers to collaborate and

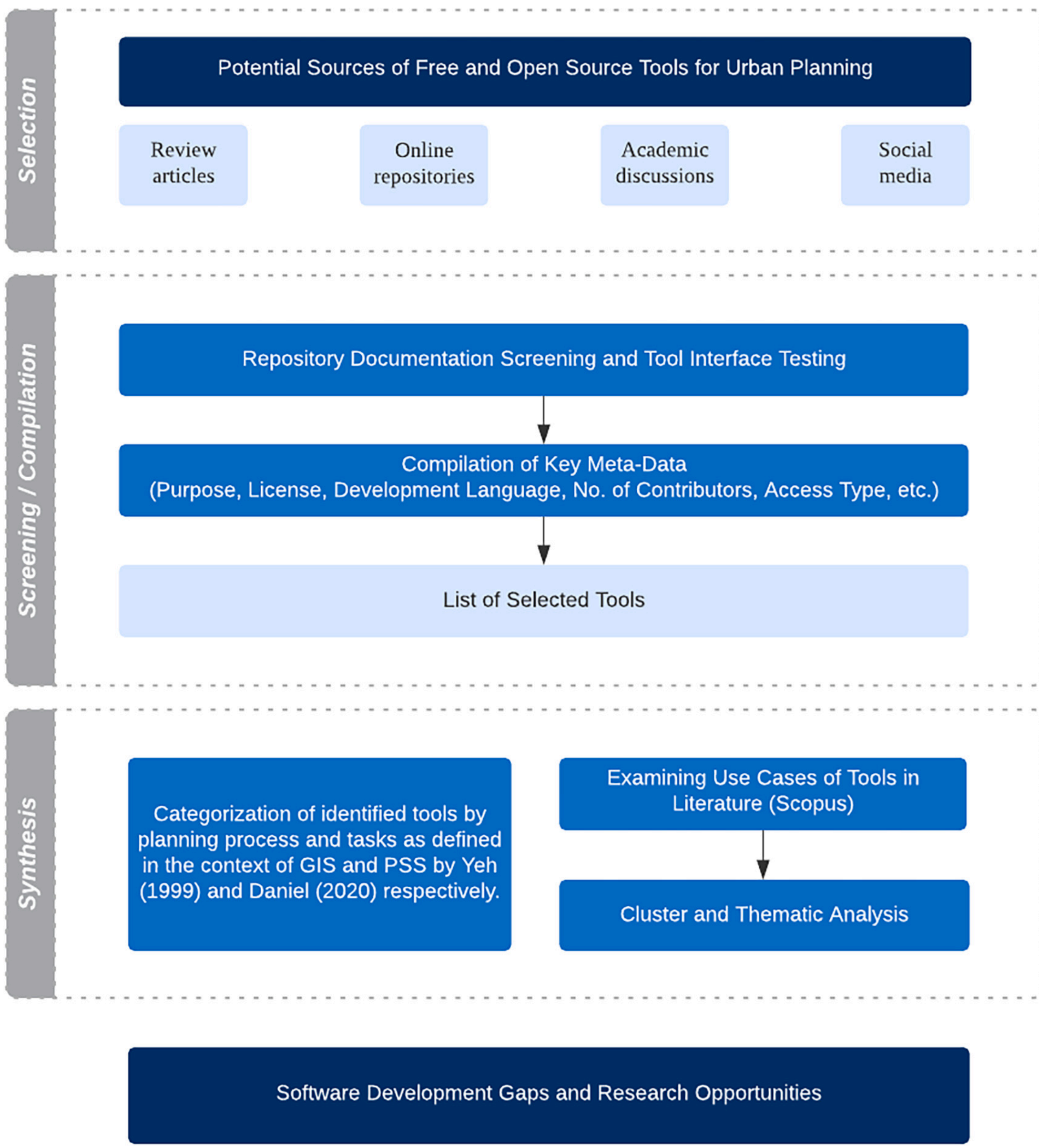


Fig. 2. Structure and methodology of the study.

share software. As of October 2021, GitHub recorded 63 million users and more than 190 million repositories, making it the largest code hosting platform in the world. Therefore, we included it as one of the main channels to identify software relevant to our review. While size does not equate to being representative, software identified through review articles and social media cross-validated almost completely (except TrajAnalytics project) with GitHub repositories. We began a snowballing search of repositories through tags such as 'GIS', 'network-analysis', 'urban-planning'. We scoped our search of repositories based on Github's popularity metric (number of stars), choosing the top 30 repositories under each tag. The process of topic tag searching and snowballing was iterated whenever new topic tags were found and adopted to ensure that the selection is rigorous and inclusive.

Second, a similar snowballing approach was adopted for review articles. We limited our search to articles classified as review papers and searched on terms including 'review', 'open source', 'tools', 'software', 'urban' through Scopus. Our latest search, which was conducted on 2 November 2021, yielded 122 review articles. After screening, 106 were excluded and the remaining 16 were screened for open source software.

Third, social media platforms such as Twitter have become popular avenues for researchers to share their research. Such information streams have emerged as an important source of information (Mohammadi, Thelwall, Kwasny, & Holmes, 2018). We conducted a search on Twitter for keywords including 'open source', 'urban', and 'tool' over the last decade. Notably, Twitter provided a high rate of return on open source software and returned several popular tools such as scikit-mobility (Pappalardo, Simini, Barlacchi, & Pellungrini, 2019), urscape (Cairns, 2018), Treepedia (Cai, Li, Seiferling, & Ratti, 2018), and review papers of open source tools for urban morphology (Fleischmann et al., 2021) and transportation planning (Lovelace, 2021). These findings suggest that social media is gaining traction as a platform for open source collaborative research.

3.3. Categorisation and thematic classification

Next, we categorised our list of software into planning process phases, application domains, and main focus. As noted by previous review papers (Biljecki & Ito, 2021), such classifications tend to be complex and may be subjective. The complexity and difficulty of this task is compounded by the highly interdisciplinary, multi-scalar (extending to different spatial scales), and eclectic nature of urban planning.

To identify thematic clusters we compiled a corpus of use case research articles and their meta-data from Scopus. We searched for use cases using the tool name as search term. For popular tools such as OSMNx, Blender or QGIS, this returned a large number of research articles (up to 300). We screened the top ten most cited articles for these software.

A factorial analysis and hierarchical clustering method was implemented on article abstracts to identify topic clusters. Following Cobo, López-Herrera, Herrera-Viedma, and Herrera (2011), a thematic mapping algorithm based on word co-occurrence was used to identify the level of development (Callon's Density) and relevancy (Callon's Centrality) of themes among applied use cases (Callon, Courtial, & Laville, 1991).

4. Results

4.1. Open source software for urban planning

An overview of the process of software screening and selection process is enumerated in Table 1. The overall search concluded with a final list of 124 relevant tools. Due to the large number of tools, we chose to split the set of tools into two lists according to their focus. This bifurcation resulted in the main list of 70 tools with direct connection to the planning process (Table 3) and a set of 54 peripheral tools that provide additional support for domains related to urban planning (e.g. energy modelling and simulation, spatial econometrics, agent-based modelling) (Table 4).

Table 1
Overview of the screening and selection process of tools.

Source[1]	Online Repositories		Review Articles[2]		Social Media	
	No. of Tools	%	No. of Tools	%	No. of Tools	%
Initial Pool	332	100	226	100	72	100
Excluded	279	84.0	202	89.4	34	47.2
Not Relevant[3]	187	56.3	110	48.7	16	22.2
Not Applicable[4]	63	19.0	40	17.7	8	11.1
Not Open Source[5]	13	3.9	37	16.4	5	6.9
Duplicates	16	4.8	15	6.6	5	6.9
Included in the review	53	16.0	24	10.6	38	52.8

[1] Repositories and tools from academic discussion are directly included ($N = 9$).
[2] A documented list of review articles is provided in Table 2.
[3] Excludes software with application domain not directly relevant to urban planning.
[4] Excludes software without analytical functionalities (e.g. data management tools or web frameworks).
[5] Excludes proprietary software, software which require paid API, and software for which its source code is unavailable.

Table 2 provides a summary of the article review process and documents review objectives of relevant review articles. Broadly speaking, review objectives can be classified into three main groups: (1) exploring the landscape of software; (2) assessing the competency of available software; (3) considering steps to improve software adoption. Most review papers address all three domains. Reviews focusing on exploring the landscape of tools typically employ either a focused (deep diving into key characteristics of selected tools) or more representative approach. As part of the exploratory effort, some reviews provide a functional classification of software typologies or describe the current state of the art and progress in software development. As part of software assessment, most papers discuss the analytical capabilities of software with respect to an application area of interest. For example, Lovelace (2021) discuss the extensibility of transport planning tools to study phenomenon across various urban scales. The papers by Wang et al. (2013); Fleischmann et al. (2021) go a step further, demonstrating how open source software can be integrated into existing case study analysis workflows. It is also common for review papers to provide recommendations to improve uptake among users. For example, Steiniger and Hunter et al. (2013) propose metrics to guide software selection for GIS education use cases. On the other hand, Anselin and Rey (2012) envision a spatial econometrics workbench (environment supporting scientific workflows) and provide a critical discussion of potential barriers and limitations to user adoption. Our review extends this list of past efforts to document open source tools, with explicit focus on software for urban planning application and use cases. We proceed to document key characteristics of the main list of software.

Github stars are a way to show support or appreciation for the work of developers, and may serve as a proxy for the popularity of a particular tool. The number of stars on a repository might even influence the willingness of community developers to contribute to a project (Borges & Valente, 2018). Similar to 'likes' on social media, stars offer a form of social feedback and user validation mechanism for software developers on their repositories. Fig. 3 displays the distribution of Github stars according to various categories. On development language, Javascript (39.4% of total) and Python (18.2% of total) emerged as the top two programming languages. The 2021 survey of programming language popularity by the PopularitY of Programming Language (PYPL) Index rates Python and Javascript as the 1st and 3rd most popular programming langugage respectively. While not positing the importance of one

Table 2
Past review articles on software and their review objectives.

Review Article	Focus	Exploration					Assess			Adoption			
		Deepdive of Subset	Mapping Landscape	Categorisation	Documenting Use Cases	Evolution of Software	Software Capabilities	Integrated Workflow	Case Study Analysis	Guide User Selection	Development Roadmap	Discuss Future Trends	Identify Software Gaps
Anselin (2012)	Spatial Data Analysis	●	–	–	●	●	●	–	–	–	●	●	–
Anselin and Rey (2012)	Spatial Econometrics	–	–	–	–	●	●	–	–	–	●	●	●
Steiniger and Hunter (2013)	GIS	–	●	●	–	–	●	–	–	●	–	●	–
Wang et al. (2013)	GIS	●	–	–	–	–	–	●	●	–	●	●	–
Allegrini et al. (2015)	Urban Energy Systems	●	–	–	–	–	●	–	–	●	–	●	–
Leidig and Teeuw (2015)	Disaster Management	–	–	●	●	–	–	–	–	●	–	●	●
Swain et al. (2015)	Urban Water Resources	●	–	●	●	–	●	–	–	–	–	●	–
Smith (2016)	Geospatial Mapping	●	–	–	●	●	●	●	–	–	–	●	–
Palomino et al. (2017)	Spatial Data Analysis	●	–	●	–	–	●	●	–	–	●	–	–
Khan, Ketzel, Kakosimos, Sørensen, and Jensen (2018)	Road and Air Pollution	●	–	–	–	–	●	–	–	–	–	–	●
Saretta, Caputo, and Frontini (2019)	Urban Energy Systems	–	–	–	●	–	–	●	–	–	–	–	–
Sola, Corchero, Salom, and Sanmarti (2020)	Urban Energy Systems	●	–	●	–	–	●	●	–	●	–	●	–
Ferrando, Causone, Hong, and Chen (2020)	Urban Energy Systems	●	–	–	●	–	●	●	–	●	–	●	–
Fleischmann et al. (2021)	Urban Morphology	–	●	●	–	●	–	●	●	–	●	●	–
Klemm and Vennemann (2021)	Urban Energy Systems	●	–	–	–	–	●	–	–	–	–	●	–
Lovelace (2021)	Transportation Planning	–	●	●	●	–	●	●	–	●	–	●	●

Final Scopus search conducted on 1 November 2021 returned 122 review articles. Upon abstract screening, 16 articles were selected. Main exclusion reasons: (1) not relevant to urban planning; (2) focus not on tools but on standards/methods or general importance of technology.

programming language over another, the popularity of Python and Javascript speak to the importance of these languages for software applications in urban planning. Geospatial analysis (43.8%) and mapping (23.8%) emerged as the areas with the highest number of stars. This finding is not surprising given the maturity of the open source GIS ecosystem where organizations such as OSGeo have been longtime supporters of open source software and standard. Among developer groups, the most number of stars were attributed to software developed by individuals (37.2%) and private companies (35.2%) respectively. These include popular tools such as OSMnx, Citybound, and the Google Earth. Tools such as kepler.gl (Uber Engineering) and CesiumJS (Cesium) were originally developed as proprietary software by private companies but later become open sourced.

A similar proxy of popularity is the number of contributors of a repository (as reported on each Github page). While the number of Github stars reflect the popularity of a repository among the external community, the number of developers indicates the level of human resources committed to different projects. Fig. 4 illustrates the distribution of developers across different categories. The largest number of contributors come from private companies and OS Community projects. These make intuitive sense as companies tend to have large, dedicated software development teams while Open Source Community projects may require a large development community to keep the software updated. The overall number of contributors for development language and access type is larger given that several repositories employ multiple development languages and provide multiple access types. For example, Orfeo Toolbox offers both a command line interface and QGIS plug-in while Place Syntax was developed with both C++ and Python.

Access type for tools can be grouped into two main categories: tools that require users to code and those that do not require coding. The latter comprise of web applications and graphical user interfaces (GUI) where the default mode of operation is a ‘point and click’ approach. Javascript application programming interface (27.6%) and web applications (27.5%) are the most popular access types among the list of urban planning tools. Of the 70 software listed in Table 3, 42 (or 60%) require users to have familiarity with coding either through a command line interface or language API (Python, R, C++ or Javascript). Such a trend is both indicative of a preference among developers for a text-based interface and how programming workflows can promote reproducibility. Non-coders currently face barriers using these tools.

4.2. Peripheral open source tools for urban planning

Urban planning is an eclectic field that draws its origins from many sub-fields such as civil engineering, transport planning, architecture, and construction. While not playing an explicit role in the urban planning process, applications and use cases from said domains often influence urban planning through the decision making process. For example, in recent years, discourse on strategic planning concepts such as the ‘sustainable’ or ‘healthy’ city draw a parallel with research development in the field of energy and climate modelling. Similarly, fields such as spatial econometrics, computer vision, and agent-based transport models have contributed a robust set of methods and tools to improve our understanding of the spatio-temporal complexity of cities. To reflect these developments, we compiled a list of additional tools for further exploration. A compiled set of open source GIS tools is also included in the extended list.

4.3. Implementation of the planning process

Urban planning operates in the domain of public administration which warrants the input and consideration of diverse stakeholder groups. Different planning scenarios and scales translate to different actionable steps for planners which makes the objective of defining planning tasks a seemingly intractable mission. Nonetheless, there has been general consensus over the main phases of the urban planning process.

Harris (1999) defines three broad areas of a planner's professional responsibility: (1) analysis (understanding impact of plans and relevance of information streams as related to locations, and deployment of professional knowledge to social and geographic spaces); (2) design (generation and consideration of different planning scenarios); (3) public participation (reconciliation of public interest with the formation of plans), defining these activities as central and the basis of wider forms of planning activity. Similarly, the process of urban planning has been outlined in the context of GIS by Yeh (1999), defining the planning process as four key steps: (1) formulation of planning vision, goals, and objectives; (2) consideration of alternatives and evaluation of plans; (3) implementation; (4) monitoring and post-implementation evaluation.

Within the context of planning support systems and software, the seminal paper by Vonk, Geertman, and Schot (2005) classifies urban planning tasks into four functional categories: information provision (provide access to input data), communication support (assist planners to convey information to non-technical stakeholders), supporting analysis functions (enable knowledge synthesis and converting data to intelligible understanding), and supporting design functions (allow exploration of design alternatives).

More recently, Daniel (2020) examines the application of computational tools to support various stages of the rationale planning process—contextual and site analysis, evaluation of planning scenarios, visualisation and public participation, and monitoring and evaluation. Notably, collaborative planning has been seen as an essential component of modern planning. For the purpose of our study, we adopt the most recent definition of planning phases outlined by Daniel (2020) in our categorization of free and open source tools. Fig. 5 presents a visual schematic of different planning phases and highlights several software relevant to each stage that we have identified in our review.

A brief description of each urban planning phase is outlined below. Phases often (but not always) proceed in the following sequential fashion:

4.3.1. Site analysis

The stage where planners familiarise themselves with the strength, weaknesses, threats, and opportunities of the site. They do so by documenting various aspects of the site through various layers, including public infrastructure, green infrastructure, road networks, building morphology, etc. The aim of this stage is to develop a strategic vision, concept plan, and planning objectives for the site.

4.3.2. Scenario planning

Scenario planning often follows from site analysis where the objective is to explore viable design alternatives to meet the requirements of the identified planning vision and objectives. This phase involves parametric studies and feasibility analysis to fine-tune and optimise policy and planning goals.

4.3.3. Public participation

Public participation or collaborative planning usually comes after the design recommendations have been constructed. These tend to be venues where planners, residents, and other stakeholders gather to brainstorm, discuss, and evaluate proposed design recommendations. It is an important aspect of the co-design process and helps to ensure that diverse voices are heard in the planning process. These events tend to take the form of community design workshops and charrettes. Public participation may coincide with the site analysis stage if public input is decided to be a key input towards planning objectives.

4.3.4. Monitoring and evaluation

Monitoring and evaluation process comes after the implementation of design recommendations. In this stage, planners examine and study whether the design intervention or policies fell short of, fulfilled, or exceeded expectations. A follow up survey of the site condition is implemented and compared to the baseline condition to determine improvements.

Table 5 provides a finer grained connection between different software and stages of the planning process outlined above. The first step is to classify tools according to a hierarchical ordering based on planning phase, application domain, and the tasks/operation level. Use cases are listed iteratively and in a ground-up fashion from our initial list of software.

While the pool of free and open source software for urban planning is expansive, there is still much room for development. In particular, a significant chasm continues to exist between theoretical discourse and the range of functions offered by tools. Notably, the representation of tools for urban planning tasks is largely skewed towards the site analysis phase. Comparatively, there are fewer tools for the scenario planning, public participation, and monitoring and evaluation phases. Recent urban planning discourse, though not in the context of computational methods, has also highlighted the need for more evidence-based approaches in the field of urban planning.

These observations have implications for the long term growth of the field. Here we agree with Batty (2021), that the study of urban planning systems should not only look at current capabilities but also examine broader trends indicative of progression in the field. As espoused by Gahegan (2018) and Poorthuis and Zook (2020), an active academic community which takes charge of the computational development and maintenance of their own software platforms allow for (1) easier access to essential methods and tools; and (2) a better representation of the diversity and heterogeneity of said disciplines. To avoid critiques of technological determinism, computational approaches should not constraint users to certain forms of analysis (by nature of tools available), but rather, allow for engagement with various phases and application domains reflective of the diverse and inter-disciplinary nature of the planning process. Subsequently, such an approach would require its users have an understanding of what the data do or do not measure, and of the results generated (Harris et al., 2017). Open source practices also improve reproducibility, replicability, and increase opportunities for collaboration in research (Boeing, 2020). While the current range of tools and application domains is expansive, many gaps and development opportunities still exist, which will be discussed in Section 6.

5. Bibliometric analysis

In this section, we aim to show how open source software is related to urban planning application and use cases. Small (1999) describes bibliometric mapping as the spatial representation of knowledge elements and domains. It is primarily occupied with delineating the contours and state of development of knowledge domains. The search was conducted on 8 December 2021 and employed an iterative search pattern for each of 70 chosen software. Search terms included software name, developer name, and ‘urban’. Returns were sorted by highest citation count and screened to identify articles that featured relevant use cases. An important caveat to the use of this representation is that the analysis is specific to the chosen set of software and would likely change depending on which software is included/omitted.

5.1. Topic clusters

A metric multidimensional scaling (MDS) method was implemented via the Bibliometrix R package (Aria & Cuccurullo, 2017), to determine the conceptual structure among software use cases. MDS remains as one of the most popular dimensionality reduction techniques for mapping thematic clusters (Börner, Chen, & Boyack, 2003). The technique works by computing a similarity metric between document pairs before applying a function which determines final mapping location by minimising the sum of squared difference between objects. Intuitively, this representation allows the embedding of an otherwise high representation (more than 2D) into a lower dimension (2D) so that it can be effectively visualised. MDS preserves the ordering of similarities between topics. Readers interested in the specifics of MDS can refer to (Van Eck, Waltman, Dekker, & Van Den Berg, 2010).

Fig. 6 shows clustering of abstract keywords based on degree of co-occurence where greater proximity of words correspond to topics being closely related. In other words, proximity on the conceptual map indicates semantic similarity and coloured clusters correspond to distinct topic fields. For example, Fig. 6 indicates that urban planning, climate change, and the built environment are closely related topics. In addition, transport planning (red cluster) is more similar to public transport (in the blue cluster) over urban form and spatial distribution.

Some interesting observations deserve attention. Across the horizontal axis, the first dimension appears to differentiate between studies employing GIS/spatial analysis or network-based approach. This observation parallels the adoption of different data models and feature representations adopted in GIS and network-based studies. While vector/raster data structures are most common in GIS, network studies tend to employ a graph-based representation. For example, topics relating to street networks, road networks, and spatial distribution fall towards the far right while GIS and spatial analysis fall to the left. Similarly, the vertical axis might reflect the scale of studies in each topic. For example, spatial distribution and urban form studies are typically conducted on a macro scale while streets networks and spatial analysis studies are usually highly localised and context-based. In the middle, urban planning, built environment, and climate change are typically examined at the urban precinct or *meso* level.

The clusters also suggest distinct differences among use cases. Not surprisingly, geographic information and spatial analysis comprise a distinct cluster with a large number of tools focused on geospatial mapping and analysis functions. The second cluster focuses generally on urban planning, climate change, travel time, and the built environment. This cluster can be interpreted as having a general focus on strategic planning for sustainability purposes and can be characterised by use cases centred around transport accessibility and sustainability in urban areas. For example, software such as Orfeo Toolbox and Geemap focus heavily on urban accessibility to healthcare facilities, urban waste management, and land-use change to predict flood risk in urban areas. The third cluster places emphasis on building footprints in cities and includes use cases examining the spatial distribution of events (e.g. traffic accidents). The fourth cluster on street networks includes use cases looking at the hierarchical structure and continuity of urban streets and relate to software such as Continuity in Street Network and OSMnx.

5.2. Topic centrality

In a extensive review of science mapping software tools, Cobo et al. (2011) suggests the use of two popular metrics: ‘Callon's Density’ and ‘Callon's Centrality’ to measure the relationship among detected clusters. Callon's Density (Callon et al., 1991), measures the internal strength of networks and can be defined as:

$$d = 100\left(\sum e_{i_j} \Big/ w\right)$$

where i and j are words belonging to the same theme and w is the number of words in a theme. This value can be understand as the theme's development or level of maturity.

On the other hand, Callon's Centrality (Callon et al., 1991), measures the degree of interaction of a network with other networks and can be defined as:

$$c = 10^{*}\sum e_{k_h}$$

where k is a word in a theme and h is another word found in another theme. This measure can be understood as the importance relative to other themes in a research field.

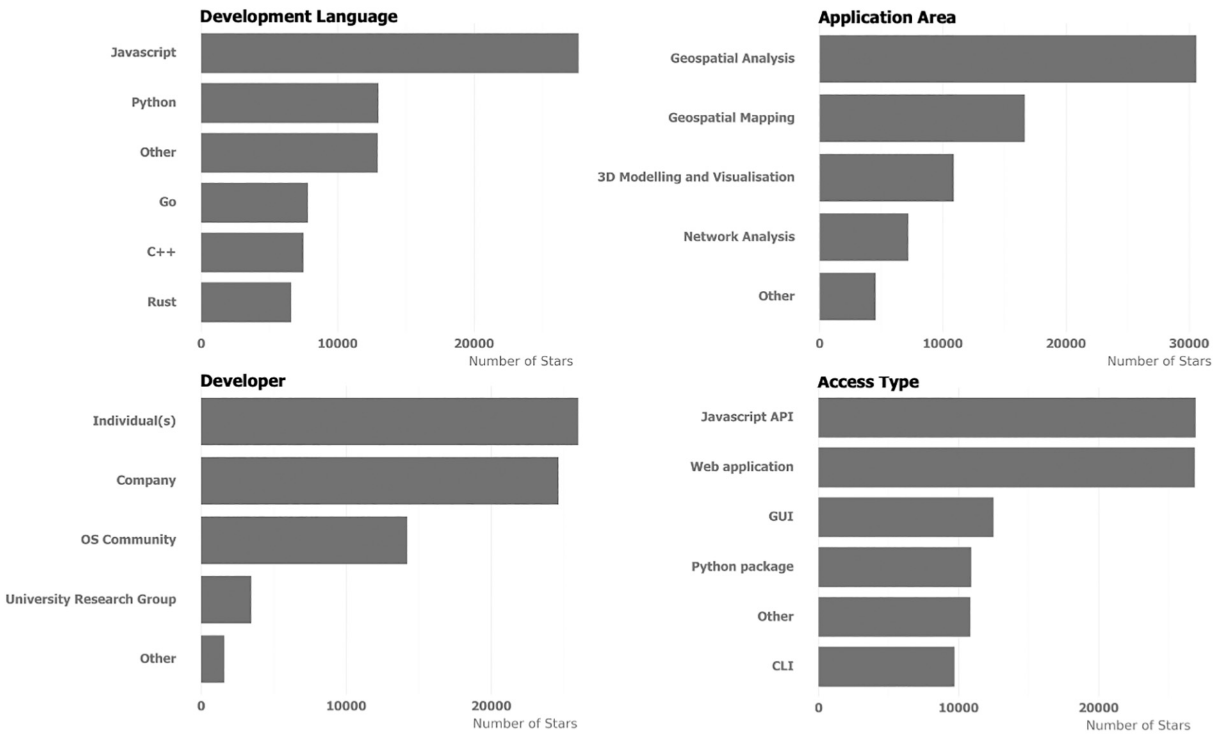


Fig. 3. Distribution of Github stars for repositories by various dimensions.

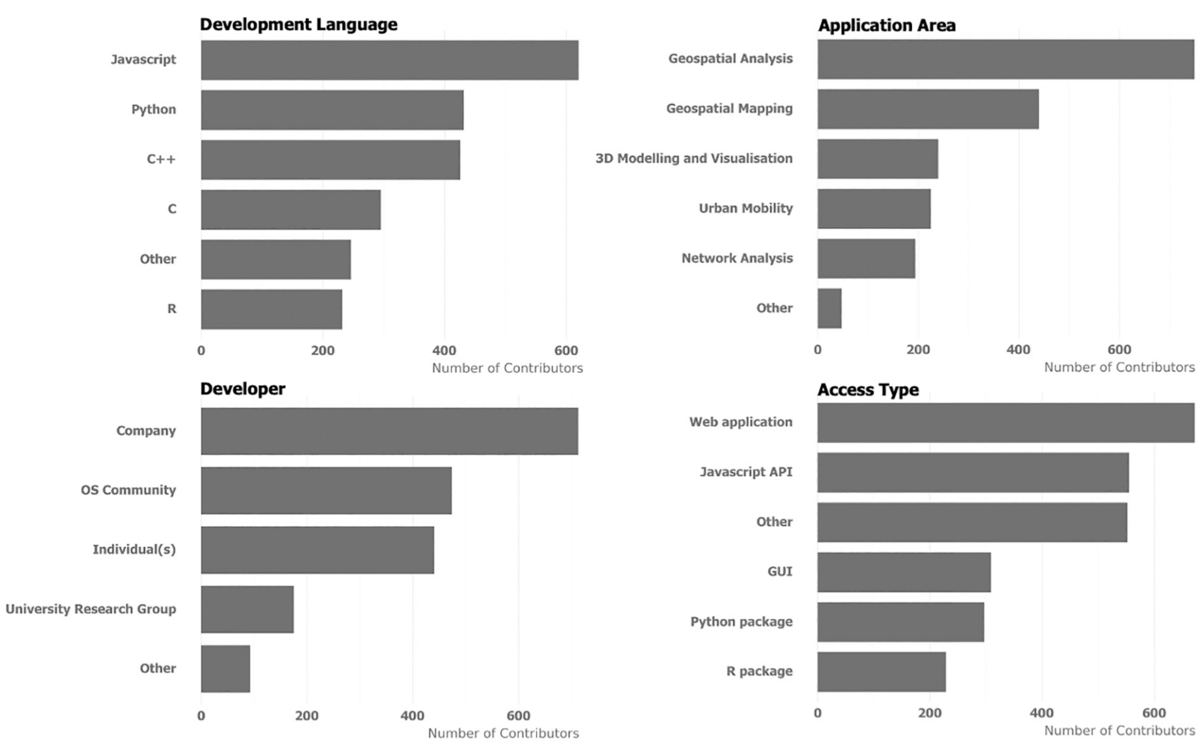


Fig. 4. Distribution of the number of contributors by various dimensions.

Fig. 7 shows the coupling map of topic clusters identified through abstract keywords. As specified by Aria and Cuccurullo (2017), the x-axis measures the cluster centrality (by Callon's Centrality index) while the y-axis measures the cluster impact by Mean Normalised Local Citation Score (MNLCS). The Normalised Local Citation Score (NLCS) of a document is calculated by dividing the actual count of local citing items by the expected citation rate for documents with the same year of publication. Accordingly, the four quadrants can be described intuitively in an anti-clockwise sequence:

5.2.1. *Upper right*

Topics in this quadrant are recognised as well-developed concepts that share strong connections with other domains in the field.

Table 3
List of open source tools for urban planning.

ID	Tool	Dev.[1]	Purpose	Access Type	Support a b c[2]	Licence	Reference
[1]	Roofpedia	RG	Deep Learning	Python API	●●●	MIT	Wu and Biljecki (2021)
[2]	Road-Network-Classification	RG	Deep Learning	Python API	●●●	MIT	Chen, Wu, and Biljecki (2021)
[3]	Citybound	I	City Modelling	GUI	●●●	AGPLv3	Citybound (2021)
[4]	Urban Growth Prediction Model	C	Land-use Planning	Python API	●●●	GPLv3	IDB (2021b)
[5]	depthmapX	RG	Network Analysis	GUI	●●●	GPLv3	Turner (2001)
[6]	QNEAT3	I	Network Analysis	QGIS Plug-in	●●●	GPLv3	Raffler (2018)
[7]	OSMnx	I	Network Analysis	Python package	●●●	MIT	Boeing (2017)
[8]	cityseer-api	I	Network Analysis	Python package	●●●	AGPLv3	Simons (2021)
[9]	graphhopper	OC	Network Analysis	Web application Java API	●●●	Apache-2.0	GraphHopper (2021)
[10]	peartree	I	Network Analysis	Python package	●●●	MIT	Butts (2021)
[11]	Place Syntax Tool	RG	Network Analysis	QGIS Plug-in Java API	●●●	GPLv3	Ståhle, Marcus, and Karlström (2005)
[12]	Continuity in Street Networks	RG	Network Analysis	QGIS Plug-in Python API	●	MIT	Tripathy et al. (2020)
[13]	spaghetti	RG	Network Analysis	Python package	●●●	BSD-3.0-C	Gaboardi, Rey, and Lumnitz (2021)
[14]	Streetmix	OC	Urban Mobility	Web application	●	AGPLv3	Streetmix (2021)
[15]	TrajAnalytics	RG	Urban Mobility	GUI	●●●	BSD-3.0	Shamal et al. (2019)
[16]	Safer-Streets-Priority-Finder	G	Urban Mobility	Web application	●●●	MIT	*City of New Orleans* (2021)
[17]	global-indicators	I	Urban Mobility	Python package	●●●	MIT	Liu et al. (2021)
[18]	PCT	RG	Urban Mobility	R package	●●●	AGPLv3	Lovelace et al. (2017)
[19]	Conveyal Analysis	C	Urban Mobility	Web application QGIS Plug-in	●●●	MIT	Conway, Byrd, and van Eggermond (2018)
[20]	Opentripplanner	I	Urban Mobility	R package	●●●	GPLv3	Morgan, Young, Lovelace, and Hama (2019)
[21]	Crash Data Explorer	I	Urban Mobility	Web application	●●●	GPLv3	Stiles (2021)
[22]	SUMO	NPO	Urban Mobility	CLI & GUI	●●●	EPL-2.0	Lopez et al. (2018)
[23]	flowmap.blue	I	Urban Mobility	Web application	●	MIT	Boyandin, Bertini, Bak, and Lalanne (2011)
[24]	MovingPandas	I	Urban Mobility	Python package	●●●	BSD-3.0-C	Graser (2019)
[25]	AequilibraE	I	Urban Mobility	Python package QGIS Plug-in	●●●	Custom	Camargo (2015)
[26]	scikit-mobility	I	Urban Mobility	Python package	●●●	BSD-3.0	Pappalardo et al. (2019)
[27]	stplanr	RG	Urban Mobility	R package	●●●	MIT	Lovelace and Ellison (2019)
[28]	Maptalk.js	C	Geospatial Mapping	Javascript API	●●●	Apache-2.0	MapTalks (2021)
[29]	Cesium	C	Geospatial Mapping	Web application Javascript API	●●●	Apache-2.0	Cesium (2021)
[30]	Field papers	C	Geospatial Mapping	Web application	●	GPLv2	Stamen (2012)
[31]	Geoplot	I	Geospatial Mapping	Python package	●●●	MIT	Bilogur (2021)
[32]	Tmap	I	Geospatial Mapping	R package	●●●	GPLv3	Tennekes (2018)
[33]	Leafmap	I	Geospatial Mapping	Python package	●●●	MIT	Wu (2021)
[34]	Barefoot	C	Geospatial Mapping	Java library	●●●	Apache-2.0	Mattheis et al. (2014)
[35]	Geemap	I	Geospatial Mapping	Python package	●●●	MIT	Wu (2020)
[36]	Osgearth	C	Geospatial Mapping	C++ package	●●●	LGPLv3.0	Pelican Mapping (2021)
[37]	3dfier	RG	3D Modelling & Visualisation	CLI	●●●	GPLv3	Ledoux et al. (2021)
[38]	3dstreet	I	3D Modelling & Visualisation	Web application	●●	AGPLv3	Farr (2021)
[39]	blender	OC	3D Modelling & Visualisation	Web application	●●●	GPLv3	Blender (2021)
[40]	Mobius	RG	3D Modelling & Visualisation	Web application	●●●	MIT	Janssen, Li, and Mohanty (2016)
[41]	Random3Dcity	RG	3D Modelling & Visualisation	Python API	●●●	MIT	Biljecki, Ledoux, and Stoter (2016)
[42]	Urban-pulse	RG	Geospatial Analysis	Web application	●●●	BSD-3	Miranda et al. (2016)
[43]	Urbansprawl	I	Geospatial Analysis	Python API	●●●	MIT	Gervasoni (2018)
[44]	PySAL	RG	Geospatial Analysis	Python package	●●●	BSD-3-C	Rey and Anselin (2010)
[45]	Orfeo	G	Geospatial Analysis	CLI, GUI QGIS Plug-in	●●●	Apache-2.0	Christophe, Inglada, and Giros (2008) Grizonnet et al. (2017)
[46]	Ur-scape	RG	Geospatial Analysis	Web application	●●●	MIT	FCL (2021)
[47]	Raster	I	Geospatial Analysis	R package	●●●	GPLv3	Hijmans et al. (2015)
[48]	Motif	I	Geospatial Analysis	R package	●●●	MIT	Nowosad (2021)
[49]	Sf	I	Geospatial Analysis	R package	●●●	MIT	Pebesma (2018)
[50]	Turf	OC	Geospatial Analysis	Web application Javascript API	●●●	MIT	Turf (2021)
[51]	Rasterio	C	Geospatial Analysis	Python API	●●●	BSD-3	Gillies (2019)
[52]	Leaflet-geoman	C	Geospatial Analysis	Javascript API	●●●	MIT	Geoman.io (2021)
[53]	kepler.gl	C	Geospatial Analysis	Web application Javascript API	●●●	MIT	Uber (2021)
[54]	Tile38	OC	Geospatial Analysis	CLI	●●	MIT	Tile38 (2021)
[55]	PyKrige	RG	Geospatial Analysis	Python package	●●	BSD-3	Murphy (2014)

(*continued on next page*)

Table 3 (*continued*)

ID	Tool	Dev.[1]	Purpose	Access Type	Support a b c[2]	Licence	Reference
[56]	Xarray-spatial	C	Geospatial Analysis	Python package	●●●	MIT	makepath (2021)
[57]	Stars	I	Geospatial Analysis	R package	●●●	Apache-2.0	Pebesma (2021)
[58]	Rgee	I	Geospatial Analysis	R package	●●●	Apache-2.0	Aybar, Wu, Bautista, Yali, and Barja (2020)
[59]	Sfnetworks	I	Geospatial Analysis	R package	●●●	Apache-2.0	Van der Meer (2021)
[60]	Kuwala	C	Geospatial Analysis	Python API	●●●	Apache-2.0	Kuwala.io (2021)
[61]	Squidpy	C	Geospatial Analysis	Python package	●●●	BSD-3	Palla et al. (2021)
[62]	Otpr	I	Geospatial Analysis	R package	●●●	MIT	Young (2020)
[63]	GeoDA	RG	Geospatial Analysis	GUI	●●●	GPLv3	Anselin (2003)
[64]	Momepy	RG	Urban Morphology	Python package	●●●	BSD-3-C	Fleischmann (2019)
[65]	Prclz	RG	Urban Morphology	Python package	●●●	GPLv3	Mansueto Institute (2021)
[66]	Foot	RG	Urban Morphology	R package	●●●	GPLv3	Jochem and Tatem (2021)
[67]	AwaP	I	Urban Morphology	QGIS plug-in	●●●	GPLv3	Pafka and Dovey (2017) Majic and Pafka (2019)
[68]	IC	I	Urban Morphology	QGIS plug-in	●●●	GPLv3	Pafka and Dovey (2017) Majic and Pafka (2019)
[69]	UrbanAccess	I	Urban Accessibility	Python package	●●●	AGPLv3	Blanchard and Waddell (2017)
[70]	Pandana	I	Urban Accessibility	Python package	●●●	AGPLv3	Foti, Waddell, and Luxen (2012)

[1] Index of developers: C—Company; G—Government; I—Individual(s); NPO—Nonprofit Organisation; OC—Open source Community; RG—Research Group.
[2] Support is indicated as: (a) Set-up Instructions; (b) Sample Datasets; and (c) Tutorials/Vignettes.

5.2.2. *Upper left*

Topics in this quadrant are highly developed (mature) but have marginal connection or impact to other concepts in the research field.

5.2.3. *Lower left*

Topics in this quadrant are either emerging or declining in the field.

5.2.4. *Lower right*

Topics in this quadrant are considered important but under-developed.

Several observations can be drawn from the topic centrality plot. For example, the location of remote sensing and movement data in the lower left quadrant could possibly be explained by the rise of computer vision use cases attributed to the increased availability of open source satellite and street view imagery data in recent decades. On the other hand, use cases for planning tools seem to be shifting away from built environment and public transportation studies towards a more integrative 'whole-of-systems' approach to understand the complexities of cities. Similarly, clusters in the upper right quadrant such as city models and space syntax are established topic fields that continue to see steady application in various fields of planning.

6. Discussion

6.1. *Observations and research opportunities*

We maintain our position on the potential of the open source ecosystem to meet the professional needs of modern day urban planners. Our survey reveals a wide variety of tools available for diverse planning application domains and use cases. The correspondence between planning stages and software clearly shows the influence of urban theory and practice in shaping the landscape of open urban data science. However, a deeper look into use cases reveal that this relationship is bi-directional. Particularly, the influence of data models, structures, and computational representations on urban planning practice cannot be understated. While computational methods can offer opportunities to improve urban planning practice, users must be aware of the ways their perceptions and thought processes are shaped by data. For example, OSM data treats all food establishments as homogeneous objects regardless of food quality. Yet urban research has shown that quality matters as much as quantity (Van Dillen, de Vries, Groenewegen, & Spreeuwenberg, 2012). Boeing and Arribas-Bel (2021) analyses how current urban analytical practices are shaped by a new urban computational paradigm and philosophy that underlie computational workflows. This finding has important implications for the new generation of urban science practitioners as they adopt analytical workflows. As described by Krizek, Forysth, and Slotterback (2009), planning practice is first and foremost a reflective craft where skills of mediation, negotiation, listening, and framing are prominent. Some of the most pioneering work in planning involve observing, feeling, and experiencing the quality of urban space (Jacobs, 1961; Whyte et al., 1980). Towards this issue, the concept of urban computational thinking is proposed. Wing (2006) defines computational thinking as a universal and fundamental skill to solve problems, optimise solutions, and design systems via heuristic and logical reasoning. Building on this idea, urban computational thinking involves asking questions such as "What urban problems are computable?", "What should be computed?", "Where is computation possible?" and "How does our choice of data structures change problem we are trying to analyse?". Moving towards a data-driven paradigm, these questions will be critical to consider.

Another noticeable trend in our list of tools is the relative scarcity of tools for planning tasks relating to evaluation, public participation, and scenario comparison. This trend reflects challenges faced in ongoing planning practice and suggests that software might not address the root problem associated with the discipline. It is likely that the sustained lack of tools for evaluation would continue to undermine efforts to promote evidence-based planning. However, urban computation might offer new perspectives and lenses to solve traditional problems. For example, while transparency and the lack of public participation has been a longstanding issue in planning practice, the introduction of reproducible and open workflows could help address this issue. It is also important to consider how programming workflows would affect participation from various non-technical stakeholders (Lovelace, 2021). Widget development tool kits such as PyQt provide opportunities to elevate the user

Table 4
Extended list of open source tools for urban planning.

ID	Tool	Dev.[1]	Purpose	Access Type	Support a b c[2]	Licence	Reference
[1]	GeoDaSpace	RG	Spatial Econometrics	GUI	●●●	Custom	Chasco (2013) Anselin and Rey (2014)
[2]	Spdep	I	Spatial Econometrics	R package	●●●	GPLv3	Bivand et al. (2015)
[3]	Sphet	I	Spatial Econometrics	R package	●●●	GPLv2	Piras (2010)
[4]	Spatstat	I	Spatial Econometrics	R package	●●●	GPLv3	Baddeley and Turner (2005)
[5]	Gis4WRF	I	Environmental Modelling	QGIS plug-in	●●●	MIT	Meyer and Riechert (2018)
[6]	UMEP	OC	Environmental Modelling	QGIS plug-in	●●●	MIT	Lindberg et al. (2018)
[7]	CitySim	C	Environmental Modelling	CLI & GUI	●●●	BSD-3-C	Walter and Kämpf (2015)
[8]	Shadow	I	Environmental Modelling	R package	●●●	MIT	Dorman, Erell, Vulkan, and Kloog (2019)
[9]	StormReactor	RG	Environmental Modelling	Python package	●●●	CC-BY-4.0	Mason, Mullapudi, and Kerkez (2021)
[10]	Hotmaps	G	Environmental Modelling	Web application	●●●	Apache-2.0	Hotmaps (2021)
[11]	Santiago	I	Environmental Modelling	Julia API	●●●	AGPLv3	Spuhler et al. (2020)
[12]	Swmm_mpc	I	Environmental Modelling	Python package	●●●	MIT	Sadler et al. (2019)
[13]	Rayshader	I	Environmental Modelling	R package	●●●	GPLv3	Morgan-Wall (2021)
[14]	uDALES	I	Environmental Modelling	CLI	●●●	GPLv3	Grylls et al. (2021)
[15]	Mesa	OC	Agent-Based Modelling	Python package	●●●	Apache-2.0	Kazil, Masad, and Crooks (2020)
[16]	AgentMaps	I	Agent-Based Modelling	Javascript library	●●●	BSD-2	Agentmaps (2021)
[17]	Matsim-libs	C	Agent-Based Modelling	GUI & Java API	●●●	GPLv3	Horni, Nagel, and Axhausen (2016)
[18]	Simultra	I	Agent-Based Modelling	GUI	●●●	GPLv3	Ito, Otsuka, Imaeda, and Hadfi (2018)
[19]	TAPAS	RG	Agent-Based Modelling	CLI	●●●	MIT	Heinrichs, Krajzewicz, Cyganski, and von Schmidt (2017)
[20]	Pycirk	I	Urban Economics	Python package	●●●	GPLv3	Donati et al. (2020)
[21]	UrbanSim	C	Urban Economics	Python package	●●●	BSD-3.0-C	Waddell (2002)
[22]	EnergyPlus	G	Energy Modelling & Simulation	GUI; C, Python API	●●●	BSD-3-like	Crawley et al. (2001)
[23]	Oemof	RG	Energy Modelling & Simulation	Python package	●●●	MIT	Hilpert et al. (2018)
[24]	Temoa	RG	Energy Modelling & Simulation	Python API	●●●	GPLv2	DeCarolis, Hunter, Sreepathi, et al. (2010) Hunter et al. (2013)
[25]	Urbs	RG	Energy Modelling & Simulation	Python API	●●●	GPLv3	Richter (2004) Stüber and Odersky (2020)
[26]	RLUR	I	Energy Modelling & Simulation	R API	●	Apache-2.0	Morley and Gulliver (2018)
[27]	TEB	I	Energy Modelling & Simulation	GUI & Python API	●●●	CeCILLv2.1	Masson (2000) Meyer, Schoetter, Masson, and Grimmond (2020)
[28]	City Energy Analyst	RG	Energy Modelling & Simulation	GUI	●●●	MIT	Fonseca, Nguyen, Schlueter, and Marechal (2016)
[29]	Calliope	RG	Energy Modelling & Simulation	CLI; Python package	●●●	Apache-2.0	Pfenninger and Pickering (2018)
[30]	ADAGE-TRAFFIC	C	Traffic Modelling & Simulation	Web application	● ●	MIT	Agade (2021)
[31]	propeR	G	Traffic Modelling & Simulation	R package	●●●	OGLv3	Office of National Statistics (2021)
[32]	Abstreet	OC	Traffic Modelling & Simulation	GUI; Web application	●●●	MIT	AB Street (2021)
[33]	CityFlow	I	Traffic Modelling & Simulation	Python API	●●●	Apache-2.0	Zhang et al. (2019)
[34]	Trip-Simulator	NPO	Traffic Modelling & Simulation	CLI	●●●	MIT	Sharedstreets.io (2021)
[35]	Veins	OC	Traffic Modelling & Simulation	GUI	●●●	GPLv2	Sommer, German, and Dressler (2010)
[36]	InVEST	RG	Urban Greenery	GUI; Python package	●●●	Custom	Sharp et al. (2014)
[37]	Treepedia	RG	Urban Greenery	Python API	●●●	BSD-2-C	Li and Ratti (2018) Cai et al. (2018)
[38]	Geosnap	G	Demographics	Python package;	●●●	BSD-3	Knaap et al. (2019)
[39]	Housing Deficit Estimation	C	Demographics	R API;	●●●	CC-IGO-3	IDB (2021a)
[40]	OurCamera	I	Computer Vision	Python API;	●●●	MIT	Bell (2021)
[41]	Rpi-urban-mobility-tracker	I	Computer Vision	Python API;	●●●	GPLv3	Wojke, Bewley, and Paulus (2017) Wojke and Bewley (2018)
[42]	Raster-vision	C	Computer Vision	Python package;	●●●	Apache-2.0	Azavea (2021)
[43]	QGIS	OC	GIS	CLI & GUI	●●●	GPLv2	Sherman, Sutton, Blazek, and Luthman (2004)
[44]	Gvsig-online	C	GIS	Web application	●●●	AGPLv3	Anguix & Daíz, 2008)
[45]	Ilwis	C	GIS	GUI, Python API	●●●	GPLv3	52North (2021)
[46]	BlenderGIS	I	GIS	Blender plug-in	●●●	GPLv3	Domlysz (2021)
[47]	Mapshaper	I	GIS	Web application & CLI	●●●	MPL-2.0	Harrower and Bloch (2006)
[48]	L7	C	GIS	Javascript API	●●●	MIT	AntV (2021)
[49]	GRASS	G	GIS	CLI & GUI	●●●	GPLv3	Neteler, Bowman, Landa, and Metz (2012)
[50]	SAGA	RG	GIS	CLI & GUI C++ API	●●●	GPLv2	Olaya (2004)
[51]	uDig	C	GIS	GUI	●●●	EPL	Ramsey (2006)
[52]	WhiteboxTools	RG	GIS	CLI, GUI, R, Python	●●●	MIT	Lindsay (2018)

(*continued on next page*)

Table 4 (*continued*)

ID	Tool	Dev.[1]	Purpose	Access Type	Support a b c[2]	Licence	Reference
				Nim API, QGIS Plug-in			
[53]	OpenJUMP	OC	GIS	GUI	●●●	GPLv2	Steiniger and Michaud (2009)
[54]	MapWindow5	OC	GIS	GUI	●	MPL-1.1	Ames, Michaelis, and Dunsford (2007)

[1] Index of developers: C—Company; G—Government; I—Individual(s); NPO—Nonprofit Organisation; OC—Open source Community; RG—Research Group.
[2] Support is indicated as: (a) Set-up Instructions; (b) Sample Datasets; and (c) Tutorials/Vignettes.

experience for non-programmers.

Furthermore, we noticed a lack of integrated functionality among the tools surveyed. Majority of tools are designed to meet the needs of a narrow and specific set of functionality. For example, tools designed for visualisation seldom include analysis and modelling functions, vice versa. (e.g. Tmap, Sf, Pandana). This makes it challenging to employ a single tool for towards project purposes and it is more likely that users will need to utilise multiple tools for different phases of the project's lifecycle. This might raise the barriers to adoption as it require users to familiarise themselves with multiple interfaces and users might face additional difficulty with extensibility (e.g. incompatible data structures) across software. While tools such as GeoDA, Place Syntax Tool, and Ur-scape provide an integrated interface, these currently form the exception rather than the norm. In addition, these tools focus explicitly on network and geospatial analysis. There are opportunities to develop tools with integrated functionalities in other application domains.

Another potential area for research is in the domain of comparative studies. Tools employ a different methodology from traditional statistical analysis. While the latter depend on methods of statistical significance to determine the generalisability of findings, it is often not possible to deduce the truth of observed parameters derived from tools. This characteristic highlights the importance of comparative studies to benchmark findings to different urban contexts. Tools such as Roofpedia (Wu & Biljecki, 2021), OSMnx (Boeing, 2021), etc., allow for cross-comparison between different localities and are fundamental to our understanding of complex urban systems.

On a more positive note, the ubiquity of urban data and the proliferation of computational tool-kits has opened up novel analytical lenses to understand the complexity of cities (Boeing, 2021; Crooks et al., 2016). Planning support tools augment planning practice by providing new mediums for urban planners to understand, model, and visualise complex urban systems. Data-driven methodologies (e.g. computer vision, machine learning, deep learning) are gaining traction and is likely to be easier to implement as data volume increases due to open, crowdsourced spatio-temporal data streams (such as street view imagery, OpenStreetMap, and satellite imagery). Some of these changes involve a fundamental shift in the way urban data is being generated and utilised. For example, Wu and Biljecki (2022) demonstrate the effectiveness of generative adversarial networks (GANs) to create building footprint data from road networks. This work addresses an important gap in data representation, particularly for regions in the global south which are often mapped with uncertain or heterogeneous quality. Similarly, generative methods have shown potential to automate steps in the complex process of designing maps (Christophe, Mermet, Laurent, & Touya, 2022; Ye, Du, & Ye, 2021). These trends point to the converging importance and collaborative nature of urban planning practice and data will likely continue to grow in abundance as more activities are being digitally recorded (Batty, 2021; Boland et al., 2021).

The landscape of open source tools is under rapid development. In the process of our review, we cross-validated software with earlier reviews and noted significant change. Several software reflected updated versions and licences which expanded their functional and shareable scope. Particularly, social media platforms such as Twitter returned more software and tools in the last two years (2020–2021) than the rest of the eight years (2012-2019). Holistically, these trends suggest opportunities for future research on the landscape of open source tools and software for urban planning.

6.2. *Issues*

In this section, we note common issues and challenges that we encountered through the review process.

6.2.1. *Representation*

By nature of free and open source collaborative workflows, developers contribute to projects from all over the world. However, the reality of representation and participation is often disparate from that of a unified global image. Notably, the degree to which users can access and contribute to open source initiatives remains largely dependent on local infrastructure and economic conditions (Kitchin, 2014; Luque-Ayala & Marvin, 2019; Verrest & Pfeffer, 2019). The under-representation of gender groups in software development also remains a key area of concern for user representation (Vasilescu, Capiluppi, & Serebrenik, 2012; Wang & Redmiles, 2019).

6.2.2. *Documentation*

While proprietary software often come with detailed user manuals and clearly defined licensing requirements, documentation for open source software is often sparse and/or loosely regulated. For example, several challenges were encountered when parsing documentation: (1) loosely coupled information displayed over multiple pages and sites, (2) missing or contradicting licence information (e.g. repository page reports a GPLv3 licence while another site for the same software displays an MIT licence), (3) lack of requirements for what needs to be displayed (e.g. in some cases readers need to decipher the focus of a particular software as it is not described). The lack of standardization can compound the difficulty required to adopt or propose a systematic workflow based on open source tools (Lovelace, 2021; Palomino et al., 2017). For example, installation processes are highly variegated among software. While it is possible to download binary versioned compilations/software

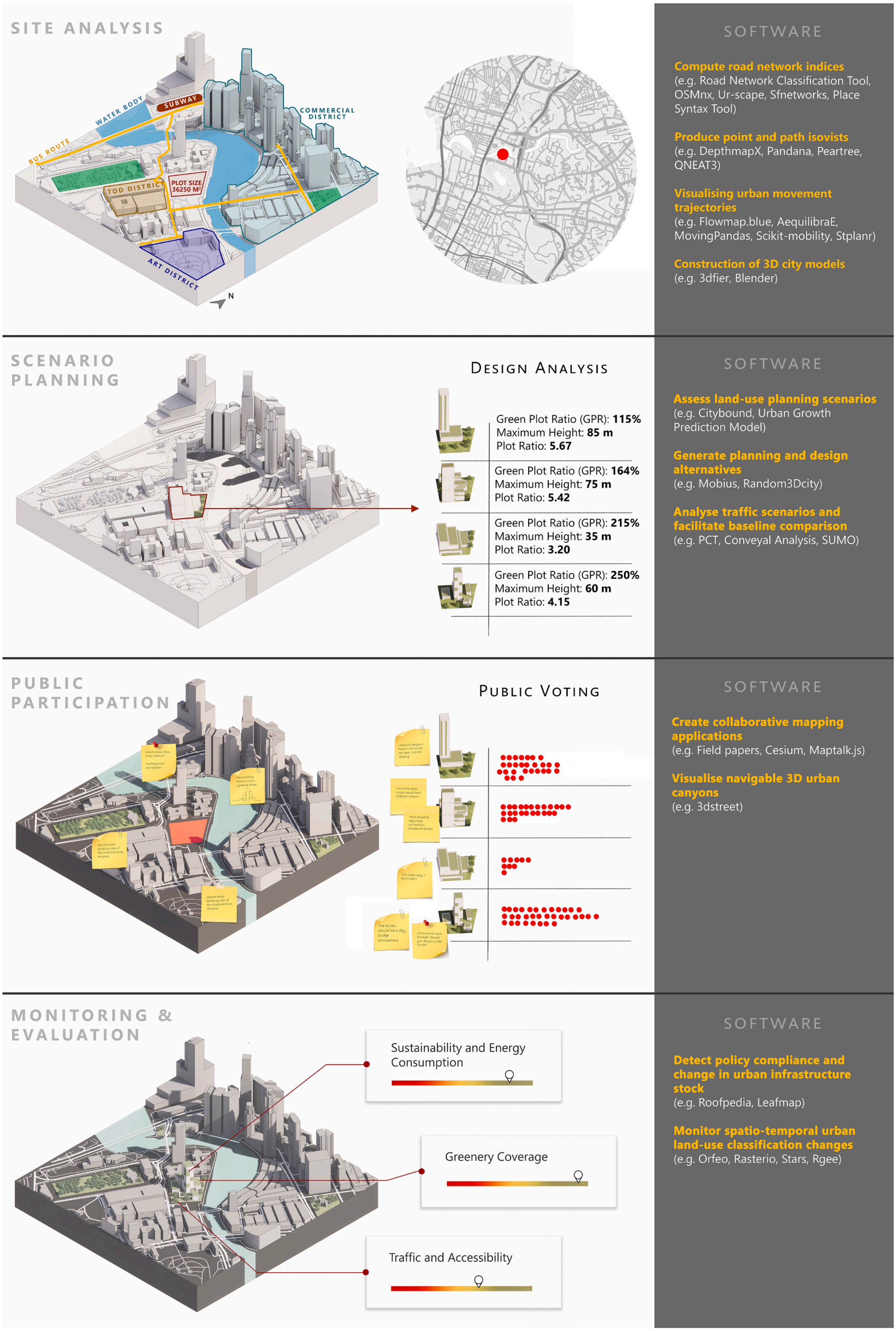


Fig. 5. The multi-stage urban planning process with examples of tasks and software tools supporting them.

Table 5
Planning process, focus, tasks, and relevant tools.

Stages / Domain	Focus	Examples of Tasks	Tools*
Site Analysis			
Deep Learning	Sustainability	Identify green/solar roofs by satellite imagery	[1]
	Road Connectivity	Compute road network characteristics	[2]
Network Analysis	Space Proximity & Accessibility	Produce point and path isovists	[5][6][7][8][9][10][70]
		Compute shortest path and centrality indices	[11][12][13][46][59]
Urban Mobility	Multi-Modal Movement	Mapping origin-destination flows	[15][17][18][19][20]
		Visualising urban movement trajectories	[23][24][25][26][27]
		Plotting multi-modal graph networks	[69]
	Road Safety & Risk	Assess network edge weighted accident probability	[16][21][26]
Geospatial Mapping	Spatial Visualisation	Map vectors and marked point pattern distributions	[28][29][31][34][63]
		Choropleth mapping spatial indicators	[32][33][35][53][63]
		Raster and tessellation classification	[35][36][58]
	On-site Mapping	Automate digitization of field records	[30]
Geospatial Analysis	Density & Placemaking	Calculate and plot dis-aggregated population data	[42][43][46][53][54]
	Spatial Statistics	Compute areal interpolation and spatial weights	[55][60][62][63]
	Vector Features	Compute point pattern indices and set operations	[44][48][49][50][52]
		Measure network topology and connectivity indices	[59][61][62][70]
	Raster Features	Implement raster algebra computations	[45][47][51][56][57]
3D Modelling & Visualisation	Built-up Environment	Assist with construction of 3D city models	[37][39][40][41]
Urban Morphology	Infrastructure & Form	Measure area diversity and site area coverage	[64][67][68]
	Building Footprints	Create figure ground vectors	[7][65][66]
Scenario Planning			
City Modelling	Feasibility Analysis	Assess land-use planning scenarios	[3][4]
Urban Mobility	Transportation Planning	Facilitate traffic scenario baseline comparison	[14][18][19][22]
3D Modelling & Visualisation	Parametric & Procedural Modelling	Generate planning and design alternatives	[40][41]
Public Participation			
City Modelling	Experimentation	Conduct hands-on simulation sessions	[3]
Geospatial Mapping	Dynamic Mapping	Create collaborative mapping applications	[28][29][30]
3D Modelling & Visualisation	3D Interactive Environment	Visualise 3D navigable urban canyon	[38]
Monitoring / Evaluation			
Deep Learning	Infrastructure Maintenance	Track policy compliance; Detect urban stock	[1]
Network Analysis	Transport Pattern	Evaluate traffic congestion over time	[10][69]
Urban Mobility	Road Surveillance	Monitoring aggregate accident statistics	[16][22]
Geospatial Mapping	Monitoring and Tracking	Analyse spatio-temporal urban change	[28][29][33]
Geospatial Analysis	Urban Activity	Measuring spatio-temporal vibrancy at urban locations	[42]
	Remote Sensing	Land-use classification, segmentation, and detection	[45][51][57][58]

* Tools are referenced and indexed from Table 3.

extension plug-ins that allow direct usage for some tools, other tools might require users to build a software container from Docker or install their software through a command line interface.

6.2.3. Long term support

A perennial concern is whether open source software will continue to be maintained and updated. Unlike proprietary software, there are no user licence and usage obligations and software is provided on an 'as-is' basis. Notably, a large proportion of open source software comprise of academic research software where research grants for software development rarely include budgeting for long term support and maintenance (Heron, Hanson, & Ricketts, 2013). Indeed, our survey of past review papers returned several tools that have been deprecated or discontinued (e.g. GeoVista, HiDe, OpenGeoDa, TangoGPS). For example, Walkalytics, an R package which used to serve as a wrapper to the Walkalytics API (providing pedestrian movement data), was discontinued because the API service ceased.

7. Conclusion

In this paper, we provided an extensive review of open source software for urban planning, through the examination of academic review articles, GitHub repositories, and social media. We have shown that there are a diverse range of open source tools to support various urban planning application domains and categorised the tools according to their relevance to traditional phases of the urban planning process with accompanying use cases. Our analyses reveal interesting patterns about the landscape of open source tools. Geospatial and network analysis remain the dominant use cases, reflecting both the historical importance of GIS development and continued relevance of emergent geospatial data and methodologies for contemporary urban studies. The landscape of tools is principally skewed towards site analysis related use cases, underlying the importance of context-based studies. Future research opportunities include the development of open source tools to support other stages of the urban planning process. In particular, tools to assist with scenario planning, public participation, and monitoring and

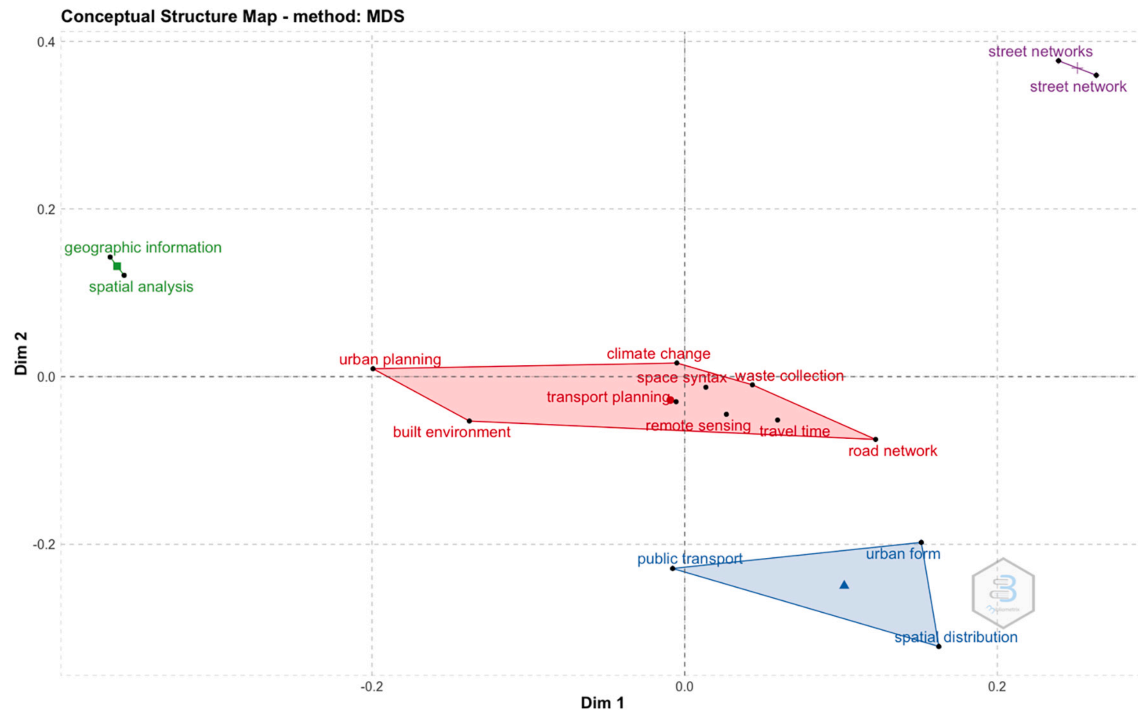


Fig. 6. Conceptual structure map.

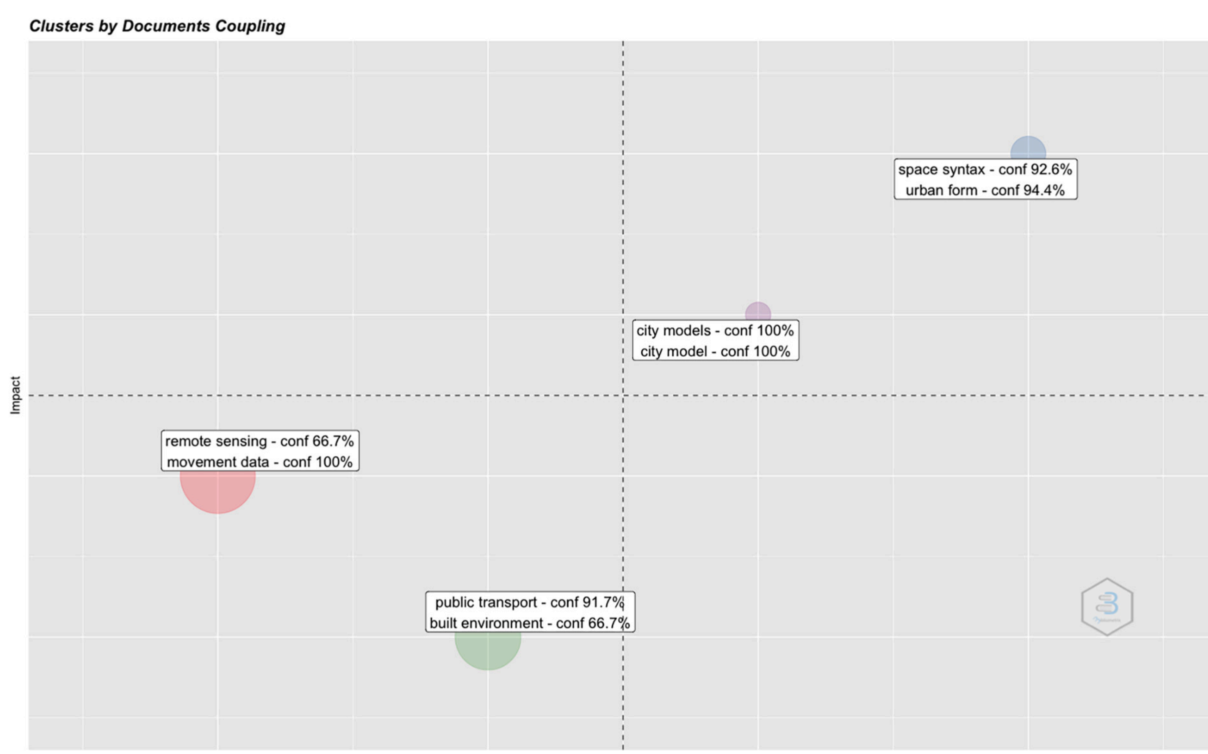


Fig. 7. Clusters by document coupling.

evaluation phases would regard calls for increased accountability and evidence-based decision making in the urban planning process. As we witness the proliferation of many new forms of urban data—not limited to, crowdsourced efforts, street view and satellite imagery—the landscape of urban analytical tools will likely continue to evolve, offering novel and diverse ways to understand and model complex urban environments.

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