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Planning support systems for smart cities

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ABSTRACT

In an era of smart cities, planning support systems (PSS) offer the potential to harness the power of urban big data and support land-use and transport planning. PSS encapsulate data-driven modelling approaches for envisioning alternative future cities scenarios. They are widely available but have limited adoption in the planning profession (Russo, Lanzilotti, Costabile, & Pettit, 2017). Research has identified issues preventing their mainstream adoption to be, among others, the gap between PSS supply and demand (Geertman, 2016), their difficulty of use, a need for greater understanding of PSS capabilities and a lack of awareness of their applications (Russo et al., 2017; Vonk, Geertman, & Schot, 2005). To address this, a review of five PSS is conducted in the context of four vignettes applied in Australia and applicable internationally. A critical review has been undertaken, demonstrating how these PSS provide an evidence basis to understand, model and manage growing cities. The results suggest that PSS can assist in undertaking key tasks associated with the planning process. In addition to supporting planning and decision making, PSS can potentially enable better co-ordination between city, state and federal planning and infrastructure agencies, thus promoting a multi-scaled approach that improves local and national data sharing, modelling, reporting and scenario planning. The research demonstrates that PSS can assist in navigating the complexities of rapid multi-faceted urban growth to achieve better-informed planning outcomes. The paper concludes by outlining ways PSS address limitations of the past and can begin to address anticipated future challenges.

1. Introduction

The integration of Information Communication and Technology (ICT) into cities over the past two decades has generated interest from urban analysts and theorists alike (Kitchin, 2014a, p. 1). Harrison and Donnelly (2011) list examples of the many potential benefits that can arise, such as: lower resource consumption, improving infrastructure capacity, and coordination of peak demands on energy, water and transportation to improve city resiliency. However, the concept of smarter city planning as enabled through big data, city analytics and modelling is one potential benefit which has not been given sufficient consideration. This paper endeavours to address this gap through reviewing recent case studies in the application of planning support systems in the context of Australia.

When considering smarter cities planning one must first provide a suitable definition of smart cities. There are many and varied definitions. Kitchin (2014a) defines smart cities as those that address technology, economy, and governance - comprised of ubiquitous computing and driven by innovation. Other definitions focus on the various scales addressed by smart cities, such as that from Batty et al. (2012), referring to smart cities as both automated "routine functions serving individual persons, buildings, traffic systems" as well as "ways that enable us to monitor, understand, analyse and plan the city to improve the efficiency, equity and quality of life for its citizens in real time" (p.482). This paper focuses on the latter portion of Batty's definition as we explore how the smart city movement has created renewed opportunity

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and interest in data-driven urban modelling to support land-use planning.

Increased automation in the built environment gives rise to big data, which is creating new potential for pattern recognition within cities (Batty, 2015). The rapid growth of big data and its range of uses means it is difficult to define (Kitchin & McArdle, 2016), but recent academic dialogue has set it apart from other data in three areas, the '3 V's': volume, velocity, and variety (Laney, 2001). The components of the multi-V model often change depending on the report (Assunção et al., 2013); other authors have defined '5 V's' (Batty, 2016; Assunção et al., 2013) or '7 V's' (Khan, Uddin, & Gupta, 2014; McNulty, 2014), encompassing the following:

- Volume – depth and breadth of data (Laney, 2001)
- Velocity – speed of transmission (Miller, 2015)
- Variety – type and kind of data (Batty, 2016)
- Variability – degree of inconsistency in data representation (Batty, 2016)
- Veracity – reliability or truthfulness of the data (Assunção et al., 2013; Khan et al., 2014)
- Validity – accuracy of the data for its intended use or application (Khan et al., 2014)
- Volatility – the relationship of the retention period for data sets with their associated storage and security needs (Khan et al., 2014)
- Visualisation – presentation of the data (McNulty, 2014)
- Value – the worth and insights derived from in-depth analysis of the data (Assunção et al., 2013; McNulty, 2014)

This paper focuses on the interpretation of big data for urban planners, primarily the *variety* of data used to assess planning scenarios, its communication to stakeholders through *visualisation* methods, and the added *value* from its addition into traditional urban modelling approaches (Thakuriah, Dirks, & Keita, 2017, pp. 189–208). The *variety* of big data we investigate are those defined by Batty (2016): data produced from real-time sensors, spatial data sensed from satellites, and data based on population and economic forecasts.

The potential to harness big data within the smart city movement creates opportunity for planners to better guide the expected 2.5 billion-person growth in the global urban population between 2014 and 2050 (United Nations, 2014). Planners can now combine population and economic forecasts with temporally and spatially sensed data through digital planning tools. Planning Support Science, a field that continuously develops and improves frameworks for big data sets, has emerged with the increased research and development of digital planning tools (Geertman, Allan, Pettit, & Stillwell, 2017). These tools, called planning support systems (PSS), use the growing presence of big data to help inform more sustainable, productive and resilient city scenarios through data mining, analysis, modelling and visualisation.

Experts believe PSS have the ability to help planners navigate the growing complexities in planning (Vonk & Geertman, 2008). Reactions to urban infill and urban growth in general are often very emotional and create anxiety about the future; Newman (2016) calls this anxiety vs agglomeration and suggests the only way to ease this is by demonstrating in each new development there are multiple benefits that can be fashioned from planned changes. It is even feasible to show how such urban growth can be regenerative to issues like climate change, biodiversity loss, bioregional water and soil issues, as well as providing new employment and services (Newman, Beatley, & Boyer, 2017). These are cultural changes in the planning system. But it will require smart PSS to enable this to happen, allowing city planning to evaluate options more thoroughly and quickly but at the same time in a more engaging way with communities. The hope is that PSS will provide a way to resolve debates of growth versus impact, of agglomeration versus anxiety, in future city planning.

Despite the availability of a range of PSS, there are issues preventing their widespread use and adoption namely, a lack of awareness of available tools and lack of experience with their implementation (Russo et al., 2017; Vonk et al., 2005). To address this concern, this paper will explore the current availability of PSS internationally, focusing on four vignettes demonstrating their application at the regional, metropolitan, precinct, and subdivision scale. These vignettes are undertaken in the Australian context yet the key learnings and recommendations from this research hold international relevance.

2. Literature review of PSS

2.1. The state of smart cities and digital planning

Land-use models were initially developed in the 1960s but became highly criticised within the same decade, largely because of the extent of data collection needed to operate them, their treatment of the city as a static system (Batty, 1971), and their attempt to model too many complexities at once (Lee, 1973). Their top-down, black box modelling approach disempowered urban planners and communities alike in the planning process (Lee, 1973). Critiques of large-scale models led to a sustained period of on-going debate between urban modellers and planning practitioners, perhaps symbolised by the close of MIT's Urban Systems Laboratory in 1974 (Townsend, 2013). GIS was instead used "almost exclusively" to analyse past and current urban conditions (Pettit et al., 2013, p. 351).

Thirty years ago, increased capabilities in micro-computing created renewed potential for digital models to guide long-term planning decision (Harris, 1989). Harris (1989) encouraged the planning industry to move beyond GIS to develop and implement user-friendly, flexible, realistic models that could rearrange data to predict impacts of planning scenarios. A call for a new, integrated framework (Gorry & Morton, 1971) led to the growth of decision support systems (DSS), which "allow decision makers to systematically generate and evaluate a number of alternative solutions" (Klosterman, 1997, p. 50). Spatial decision support systems (SDSS) are one type of DSS, and they usually build on GIS to model and visualise the optimal spatial locations for land uses (Densham & Rushton, 1988; Klosterman, 1997). PSS differ in that they are information technologies used specifically to assist the planning profession (Klosterman, 1997) and like SDSS, often integrate GIS (Geertman & Stillwell, 2009). Geertman and Stillwell (2004) define PSS as a framework that combines:

- Identification of the planning challenge;
- A methodology to guide planning through "analysis, prediction and prescription" (p.293);
- The application of data to inform modelling and design.

PSS initially focused on urban economic and travel-demand modelling (Harris & Batty, 1993) and emerged more comprehensively into the planning field the 1990s (Geertman & Stillwell, 2009). Land-use transport models were developed over the next two decades, and by 2004, at least twenty had been calibrated and implemented (Wegener, 2004). These models offer a mathematical way to isolate and combine the variables impacted by land-use and transport policy, offering more informed predictions than could be obtained from user surveys or empirical observations (Wegener, 2004).

PSS are not the only technology supported approach being used to innovate the urban planning process. Grassroots approaches like civic hacking, which uses open source technology to connect individuals to one another and their surrounding environment (Townsend, 2013), are creating disruption to city operations. Both user-friendly, inexpensive microcontrollers and smartphone app-building are allowing ordinary citizens to become entrepreneurs and city shapers. This is creating an entirely different trajectory of smart city development, especially given the ability of these decentralised developments to spread virally (Townsend, 2013). The disruption caused by civic hacking seems to be a competing strategy to top-down centralised models that seek to optimise decision-making in cities. Townsend (2013), in his review of technological innovation in city planning, notes that any top-down efforts to shape cities will require bottom-up participation.

Large private technology companies, on the other hand, piece together technological innovations that do not seem to align with researcher and community cries for bottom-up city evolution (Townsend, 2013). Companies like IBM, Cisco and Siemens are impacting smart city development by integrating new technologies into cities such as “the Internet of Things, predictive analytics, and ubiquitous video communications” (Townsend, 2013, p. 110). In 2011, IBM created a DSS software called ‘System Dynamics for Smarter Cities’ which intended to guide implementation of Portland's 25-year strategic plan using a series of 3000 analytical equations – although, as critics suspected, it did not have a significant impact on policy (Townsend, 2013). The model did allow for citizen interaction through a web interface, which serves an example of IBM's efforts to include more inclusivity in their initiatives. However, their motives may be to appease critics instead of genuine reform of top-down modelling approaches (Kitchin, 2014), which means the true concerns of society may not be reflected if the models are profit-driven rather than citizen-driven. Townsend (2013) recommended that these large-scale models learn from other modelling efforts that take a more bottom-up approach by modelling individual interactions and assessing their combined impact, which is more reflective of the way cities operate (Batty, 2012). Another notable concern is that the companies are not in the business of providing open data and open modelling tools. Thus, the ability for bottom-up involvement in smart city planning through the use and adoption of corporate approaches is often significantly limited.

PSS attempt to merge bottom-up and top-down planning processes by facilitating discussions around scenario-planning that involve the interests of various key stakeholders including city planners, policymakers, experts and communities. Our research focuses on PSS because, although it has become a “serious academic subfield” (Pelzer, Geertman, van der Heijden, & Rouwette, 2014, p. 16), PSS are underutilised in the planning industry (Geertman, 2016).

2.2. International overview of PSS tools

PSS have been widely researched and developed, primarily by academics. Private sector and government involvement in the development of PSS has remained relatively low with limited commercial off the shelf (COTS) software available for use. Although many PSS are academic prototypes with beta releases, some have been growing in use such as ‘What If?’ (Pettit et al., 2013), UrbanSim (Waddell, 2002) and UrbanFootprint (Schmiedcke, 2016). What If? has been available for the last twenty years (Geertman et al., 2017) and in that time has evolved from a desktop to an online application, making it accessible to a wider audience. UrbanSim was developed after a 1995 conference hosted by the Travel Model Improvement Project (TMIP) to address limitations of land-use modelling (Waddell, 2002) and has since continued to address challenges of urban land use, environmental and transportation planning (Waddell, 2011). Prebuilt models at Census block detail for the United States have already been released, and models at zone or parcel level will shortly be released for other parts of world (UrbanSim Inc, 2017). UrbanSim has been applied in the context of Australia, specifically in South-East Queensland (Biermann, Pettit, & Brits, 2015). It is open source, accessed at http://www.urbansim.com/platform. UrbanFootprint, designed by Calthorpe Associates in Berkeley, California, has been widely used in North America; for instance, it has recently been used to assist Madison, Wisconsin in guiding its 10-year land use, infrastructure and finance strategies (Schmiedcke, 2016). UrbanFootprint is a modelling framework for data development and organisation, as well as land-use planning, modelling, and analysis. It is fully built on open-source platforms and tools, available at http://calthorpeanalytics.com/index.html#software.

Several land-use transport integrated (LUTI) models have been used for research and pilot projects, with some real-world application. CommunityViz®, a COTS software (Klosterman, 2005), is one of the earliest PSS developed and compares scenarios against user-defined benchmarks (Trubka, Glackin, Lade, & Pettit, 2015). It is a GIS-based PSS, as is ENVISION (Russo, Lanzilotti, Costabile, & Pettit, 2018), which was designed to help identify greyfield sites for redevelopment and aid community and stakeholder engagement (Newton & Glackin, 2013). ESP is the 3D counterpart to ENVISION and conducts analyses at a smaller scale (Trubka et al., 2015). ESP was recently used to guide the White Gum Valley development in Perth, and the government developer suggests that helped it go from ‘not in my backyard’ (NIMBY) to ‘please in my backyard’ (PIMBY) (Newman et al., 2017). The Cube suite of modelling software includes six tools (CitiLabs, 2017). Cube Voyager builds macroscopic regional models to understand large scale personal travel demands (CitiLabs, 2017). Cube Land is an economic land-use forecasting software which can be used in conjunction with a transport demand model to look at the interaction of real estate markets and transport systems (Clay, White, Holley, & Curry, 2012).

Many additional PSS have been identified; for instance, Trubka et al. (2015) listed urban modelling and visualisation PSS tools including Urban Canvas, CityEngine, Precincts, Envision Tomorrow, NASA World Wind, and Google Earth. Papa, Silva, te Brömmelstroet, and Hull (2016) reviewed the widespread availability of Accessibility Instruments (AIs), which investigate land-use transport integration through a lens of accessibility, listing twenty-one different tools developed in Europe and Australia. A survey by Vonk et al. (2005) listed thirty-four available PSS. Research is growing to increase their real-world application; for instance, the Spatial Decision Support (SDS) Knowledge Portal provides continuously growing literature and case studies to guide PSS use (Spatial Decision Support Consortium, 2017). The Australian Urban Research Infrastructure Network (AURIN), a federally funded e-infrastructure initiative tasked with providing a unified space for built environment research, provides a centralised location for access to data from different agencies as well as access to a range of PSS (Sinnott et al., 2014). There are currently 100 different PSS on AURIN's online resources page (AURIN, 2017; Russo et al., 2018).

2.3. Issues preventing the mainstream use of PSS

Despite the widespread availability of PSS, the maturation of PSS software packages over the last 15 years, and their demonstrated abilities to improve planning outcomes, their uptake has been low (Geertman & Stillwell, 2004; Geertman, 2016). Geertman refers to this as an “implementation gap”, a “discrepancy between supply and demand” (p.1). A recently conducted international interview confirmed that PSS are not often used “because they do not properly fit user needs, they are considered difficult to use, and they lack transparency and reliability” (Russo et al., 2017, p. 2). Waddell (2011) adds to this, listing various conflicts of integrated land-use and transportation planning, among them the risk of non-compliance with land-use and environmental policy. Pelzer et al. (2014) note the lack of “systematic and rigorous attention to the added value of PSS for planning practice” (p.16). Vonk et al. (2005) summarise some of these ‘bottlenecks’ preventing PSS adoption into three categories: lack of awareness among planners, unawareness of PSS benefits, and low intention to start using PSS (Vonk et al., 2005).

Since most planners are currently unaware of PSS (Russo et al., 2017), training the next generation of planners will help bridge the gap between PSS availability and adoption. Master's degree programs are beginning to adopt urban science programs. These include the Master in City Sciences at Universidad Politécnica de Madrid, the MSc in Smart Cities and Urban Analytics at the University College London, the MSc in Applied Urban Science and Informatics at New York University, and the Master of City Analytics at the University of New South Wales. Geertman (2016) suggests increasing PSS courses as a way to train planners to “judge the appropriateness of PSS for a certain planning issue” (p. 3), and some are starting to emerge such as The University of Melbourne's Urban Informatics course and the University of New South Wales' Digital Cities course.

In addition to addressing currently identified bottlenecks, PSS also must address anticipated future challenges. As they evolve, PSS need to offer a balance of complexity and simplicity: a model that can handle the growing number of dimensions stakeholders are interested in ‘testing’ but that can also visualise and summarise impacts in a way that is understood (Geertman, 2016). The challenge of increasing PSS use in practice is made more difficult with the need to balance creativity and control, as well as facilitating co-ordination between those responsible for PSS adoption and for PSS implementation (Vonk & Geertman, 2008). Finally, researchers must be conscious of the impacts that optimisation and automation have on the broader operation of the city. We have learned that technocratic models of the past do not work; a city cannot be reduced to a series of optimised equations. As “urban societies are increasingly becoming socially and spatially fragmented and polarized” (Wegener, 2004, p. 139), PSS face the challenge of not only analysing specific measurable variables but also addressing broader spatial impacts on environment and equity (Wegener, 2004). The vignettes reviewed in this paper therefore discuss PSS as tools as a method of planning assistance, not a strict method of planning optimisation.

3. Methods

Research surrounding the PSS implementation gap is reaching saturation point. Instead, there is a need to focus on successful applications (Geertman, 2016), and here we present four. The PSS tools we selected have all been researched, developed or applied by the authors. This research expands on the following case studies:

(i) AURIN Portal (Pettit, Tice, & Randolph, 2017);
(ii) What If? (Pettit et al., 2015);
(iii) ENVISION and ESP (Glackin, 2012);
(iv) CommunityViz® (Lieske, Lyons, Wall, & Wall, 2008).

PSS operate at a variety of scales and focus efforts differently (Geertman & Stillwell, 2004), and there is a need for more selective applications in practice. This paper guides readers in just that, by presenting four different applications. It guides planning professionals in selecting an appropriate PSS, based on the scale of the issue and the type of analysis sought. We expand on the case studies listed above but present them as more streamlined ‘vignettes’, formatted similarly to allow for comparison. In each vignette, we research and summarise the following: the PSS tool, a planning challenge faced by a major Australian city, how the PSS tool is engaged to address the planning challenge, and insights gained to guide future city growth. In some cases, the learned insights or results have not yet been applied to change policy or city operation; this process will take time, and the authors are still actively engaged in working with each city to best apply the results. Instead, these vignettes focus on the analyses that PSS are capable of providing to facilitate evidence based decision making in cities, involving multiple stakeholder interests.

The five PSS (which are summarised in the context of the four vignettes) differ in their scale of application, openness of data and platforms, and method of visualisation, as listed in Table 1. What If? and ESP are open source, and links to their websites and source code are provided. The ESP website includes a video tutorial to guide first-time users (AURIN, 2017a).

Our research uses a qualitative mixed methods approach, comprising:

- Case study research – Since the applications of PSS can be creatively applied to a variety of urban challenges, we present short case studies, or vignettes, to serve as examples to planning professionals in the appropriate selection and application of PSS. Case study research in the urban planning industry not only assists in collecting relevant content for training courses but also in understanding the motives of various stakeholders in shaping cities (Taylor & Wynn, 1980).
- Critical review – We critically review the application of PSS in four different cities to assess their potential to address broader challenges that come with rapid urbanisation and the goal to develop sustainable, resilient, equitable cities. In addition, we assess their strengths and weaknesses to inform future development.

4. PSS in practice: 4 vignettes

Globally, the United Nations' New Urban Agenda (United Nations, 2017) outlines a series of commitments towards sustainable urbanisation, five of which emphasise the need for increased data analysis in spatial planning. Nationally, Australia's 2016 *Smart Cities Plan* and *City Deals* include the need for digital tools to be developed for Australian cities to remain competitive, inclusive and sustainable (Commonwealth of Australia, 2016); governance reforms prioritised by the Council of Australian Governments (COAG) also call for greater data transparency. PSS can help achieve national objectives such as those outlined in the *Smart Cities Plan's* three pillars: smart investment, smart policy and smart technology (Commonwealth of Australia, 2016).

In Australia, state-based legislation shapes planning decisions, and the following PSS applications can be considered as part of a suite of digital planning tools which add a data-driven evidence basis to state and local planning decisions. Sydney, Perth, Melbourne, and Brisbane are expected to absorb almost 10 million new residents by 2050, creating a need for improved planning processes to handle rapid urbanisation. Therefore, for each city, our researchers applied a PSS to address one of the urban planning challenges, as listed in Table 2.

4.1. Regional application (Sydney – AURIN portal)

4.1.1. AURIN portal

The Australian Urban Infrastructure Network (AURIN) is an eResearch initiative “to establish an infrastructure network to support the urban research, policy and decision-making community” (Pettit, Glackin, & Trubka, 2014, p. 47). AURIN is not a tool for creating future city plans, rather it can help with the analysis and benchmarking of current urban performance. The AURIN workbench holds over 1800 datasets from more than thirty providers (Pettit et al., 2017). Its primary application is the AURIN Portal, which allows users to combine many different datasets through “analytical, modelling and visualization tools” (Stimson, Tomko, & Sinnott, 2011, p. 236) thus offering researchers great scope and creativity to seek out interesting patterns that future strategic plans may wish to retain, strengthen or rectify. In essence the AURIN portal is a gateway to urban data and visualisation tools available to the urban research community (Sinnott et al., 2014).

4.1.2. Application in Sydney

In 2014, Sydney's state government released *A Plan for Growing Sydney* (NSW Government, 2014) to guide land use and planning decisions for an increasing population over the next 20 years. The plan is rooted in a series of goals to achieve its vision, focusing on: a competitive economy; housing choice; well-connected, healthy communities; and a sustainable and resilient environment. Delivery of these goals is further outlined by a set of actions that seeks to address complex interrelationships, involving efficient movement between home and work and development of a variety of housing options.

One of the challenges in implementing *A Plan for Growing Sydney*'s goals is Sydney's growing housing affordability crisis. The Australian Bureau of Statistics (ABS) reported an 82% increase in Sydney's median house price from 2001 to 2014 and a 46% increase in incomes from 2001 to 2011 (Pettit et al., 2017), indicating quickly increasing

Table 1
A comparison of PSS uses and features.

Digital Planning Tool	Scale of Analysis/Predominant Use	Open Source?	Visualisation Capabilities	Accessed at
AURIN Portal	Supports research and policy with a platform for precinct-level PSS and federal datasets	Some parts	2D maps, brushing	Website: https://aurin.org.au/workbench/ Access: The AURIN Portal is accessed through the AURIN workbench and is available to universities and research institutions.
What If?	Municipal and city level to test growth scenarios	Yes	2D maps	Website: https://aurin.org.au/projects/portal-and-infrastructure/what-if/ Open Source Code: https://github.com/AURIN/online-whatif Access: Create account
ENVISION	Precinct and subdivision level to identify areas for infill	No	2D maps	Website: https://aurin.org.au/projects/lens-sub-projects/envision/ Access: Available with CRC SI approval
ESP	Subdivision and parcel level to assess redevelopment scenarios	Yes	2D maps, 3D maps	Website: https://aurin.org.au/projects/lens-sub-projects/esp/ Open Source Code: https://github.com/AURIN/esp Access: Available through CRC SI
CommunityViz®	City, precinct and subdivision level to develop preferred growth scenarios	No	2D maps, 3D maps, brushing	Website: http://communityviz.city-explained.com/communityviz/index.html Access: Available for purchase

affordability issues. The AURIN Portal was used to break typical broad regional generalisations about affordability (Pettit et al., 2017) into localised differences. The following data was drawn into the Portal through various pre-defined Data Hubs, which monitor the quality and usability of data sets:

- The NSW Rental Bond Board data provides annual median rent data, categorised by dwelling type and number of bedrooms, at the ABS's Statistical Areas 2 (SA2) level, which are census tracts that contain 3000 to 25,000 people or about 15,000 properties.
- The Australian Property Monitors (APM) dataset has 20 years of spatial-temporal data on dwelling types, updated monthly. Its approximately 5.6 billion records have been aggregated to 12 spatial levels, which correspond with Australian Bureau of Statistics (ABS) and Australia Post standard geographies.

Since both Census and market-derived data sets are aggregated in the AURIN portal, comparisons can be reliably made across geographical levels. Credentialed researchers accessed the Portal to compare affordability in 2006 and 2011 for SA2 areas. During that time period, Sydney as a whole showed a 40% increase in median rents and a 21–25% increase on household income spent on rents.

Using the Portal, local differences were identified using the 30:40 indicator, which measures housing stress by identifying households in the bottom 40% of the income distribution that spend more than 30% of their income on housing. Using the APM data set, the median sales price from each SA2 area was broken down from 5th to 95th income percentile. The ratio of the 30:40 threshold and local median sales price provided researchers with a much more detailed picture of affordability in Sydney, as demonstrated in Fig. 1. Blue indicates most affordable and red indicates most unaffordable. Areas were identified that were only slightly above the 30:40 threshold (yellow or light green colours) despite being in larger regions that were labelled as severely unaffordable at the 40th percentile, noted by the cluster of red and orange in Fig. 1 (Pettit et al., 2017).

Affordability was also analysed over time; researchers used AURIN's data sets to plot the relationship between rent increases and income to rent ratios from 2006 to 2011 (as shown in Fig. 2), confirming that rents are increasing disproportionately faster than income. AURIN also displays the data spatially, showing locations with greatest affordability concerns (indicated by red 'class 5' shading in Fig. 2), Sydney's middle suburbs. The Portal's bounding box allowed researchers to define areas where affordability fell significantly between 2006 and 2011 and begin to extract local information identifying which types of affordable housing properties (one-bed, two-bed, etc.) have been declining, as shown in the bottom image in Fig. 2. AURIN allows researchers to interpret data in a variety of ways, ranging from plots to regional maps to fine-grain visualisations.

The analysis provided data-driven evidence to inform conversations on topics such as: how affordable housing loans might differ for different segments of the population; and where the hot spots of housing affordability are located within the city. This information can guide *A Plan for Growing Sydney's* goal to increase affordable housing levels as part of the 664,000 new dwellings that are expected by 2031 (NSW Government, 2014).

4.2. Metropolitan application (Perth – What If?)

4.2.1. What If?

Developed initially as a desktop application in the 1990s, What If? has been updated and re-engineered as an online application (Pettit et al., 2013). The original desktop What If? 2.0 planning support system has been used by over 150 users in 22 countries. The online What If? Application is an open source GIS-based PSS designed to support the land planning process. It does so by conducting land suitability analyses, projecting future land-use demand, and allocating the projected demand to suitable locations based on a range of planning criteria. The first application of the online What If? PSS has been developed and tested in the context of the Perth to Peel Region in Western Australia (Pettit et al., 2015). The original What If? has also been used to assist other cities and regions across Australia in understanding land-use supply, demand and likely future land-use change scenarios including

Table 2
An overview of the 4 vignettes that follow.

Scale of analysis	City analysed	State	Digital Planning Tool(s)	Challenge addressed
Regional	Sydney	New South Wales	AURIN Portal	Understanding regional affordability issues at a fine-grain scale
Metropolitan	Perth	Western Australia	What If?	Scenario-testing to evaluate land-use supply vs. ecology
Precinct	Melbourne	Victoria	ENVISION; ESP	Identifying areas for infill in middle suburbs
Subdivision	Brisbane	Queensland	CommunityViz®	Reviewing impact analyses with community organisations to assess development scenarios

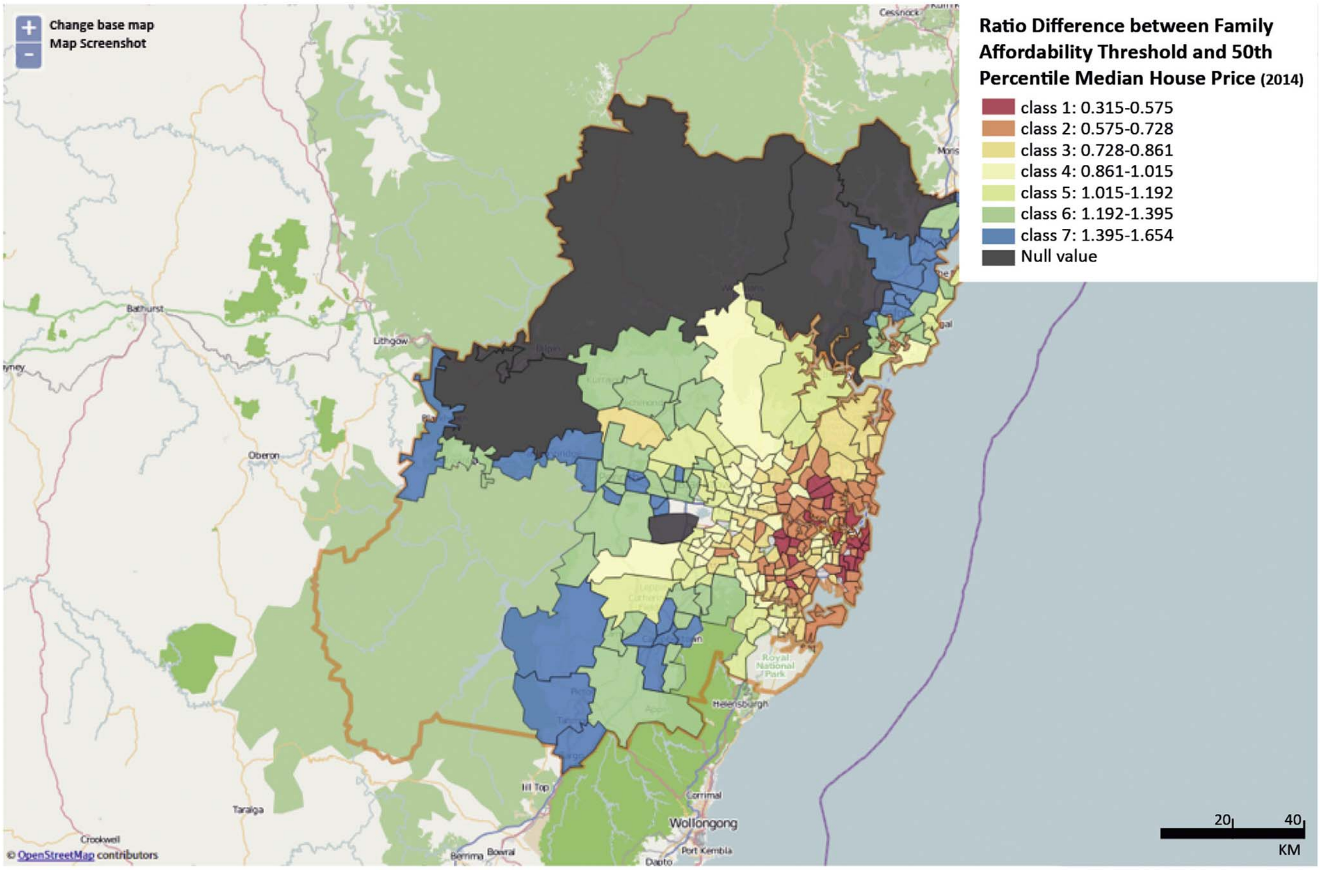

Fig. 1. The Portal's granular analysis of the ratio of 30:40 mortgage calculations to median house prices (Pettit et al., 2017).

in Melbourne (Pettit, Keysers, Bishop, & Klosterman, 2008) and Hervey Bay (Pettit, 2005).

4.2.2. Application in Perth

Perth's population is projected to be 3.5 million by 2050, a rapid expansion from its 2010 population of 1.65 million, which may impact its regional ecological assets (Pettit et al., 2015). To guide this growth sustainably and prepare strategic land-use planning for co-ordinated growth, the Western Australian Planning Commission released the draft *Perth and Peel@3.5 million* suite of documents in May 2015 (WA Government, 2015). *Directions* 2031 (WA Government, 2010) is the most recent high-level spatial framework and strategic plan to outline a vision for metropolitan Perth (the Perth and Peel region) which guides the strategic direction of major planning elements including housing, infrastructure and services. Its goals emphasise long-term affordable housing provision, ecosystem protection and economic growth planned alongside a sustainable transport network.

'What If?' was used as a tool to 'test' scenarios, specifically to balance seemingly competing goals within Perth's strategic plan: ecosystem protection and economic growth. It focused on generating two scenarios for the Metro North West region – an *employment generator scenario* and an *environmental conservation scenario* (Pettit et al., 2015). The employment generator scenario aimed to reduce commuting times for residents while seeking to protect environmentally significant areas, but only as required by planning regulations. The environmental conservation scenario classifies any areas of environmental significance as 'not suitable for development'. The 'What If?' tool evaluates land suitability based on a series of variables defined by users, as shown in the 'suitability factors' input box in Fig. 3, allowing cities to select the factors that are most contextually-important to them. Each variable is assigned a weighting to rank its importance to stakeholders. In Perth, workshops were held with the strategic land-use planners and associated domains experts to determine the key variables to 'test' and their weight of significance.

What if? contains three modules:

(i) Land suitability module: Spatial data layers created opportunity and constraint layers
(ii) Land demand module: Demographic, housing and employment project information
(iii) Land-use allocation module: Existing zoning, transport and other infrastructure plans

Once information was entered into all modules, data collection, geoprocessing and cleaning was done in a GIS package, and the resultant Uniformed Area Zone (UAZ) file, which is stored as a Shapefile, was then loaded into the What if? tool. The resultant GIS data and report CSV, a tabular data file that can be imported to Excel, were downloaded from What if? and then viewed in a standard GIS package. The employment generator scenario showed 5500 ha of land was suitable for high-density residential development, while the environmental conservation scenario showed only 1400 ha suitable for high-density residential development. Each scenario also allocated future residential land use in 5 year increments; Fig. 3 displays the residential land use allocation for southwest Perth to 2051. What if? provided useful metrics for planners to test the short and long-term impacts of each scenario, balancing it with environmental impact analyses. It provided planners with a list of concrete interventions that can be implemented to work towards *Directions 2031*'s goals of ecosystem protection and economic growth.

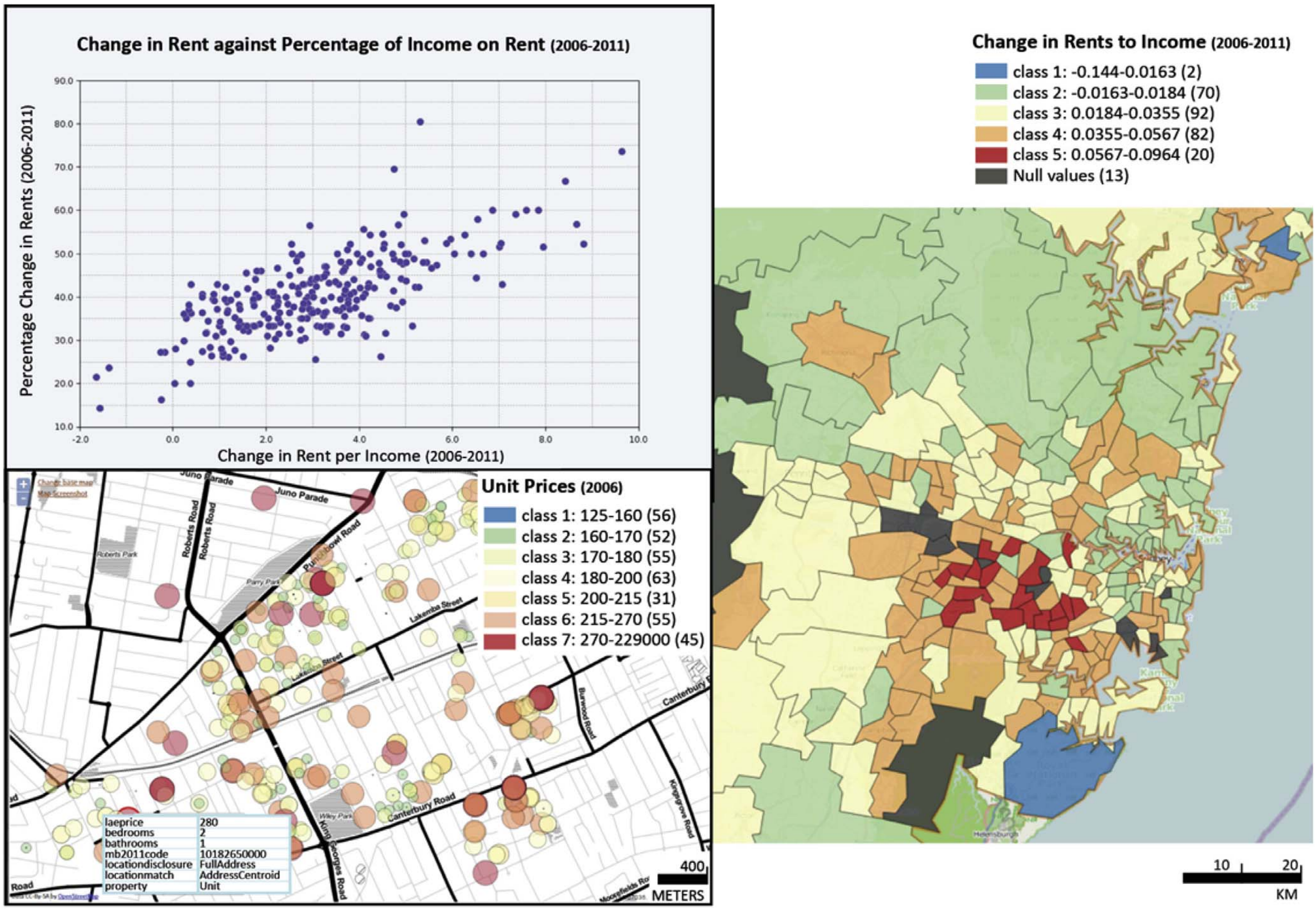

Fig. 2. The Portal's analysis of affordability changes from 2006 to 2011 with the same data presented on a scatter plot (top), a map highlighting Sydney's middle suburbs as those most quickly decreasing in affordability (right), and a local analysis of specific unaffordable properties within Sydney's middle suburbs (bottom).

4.3. Precinct application (Melbourne – ENVISION and ESP)

4.3.1. ENVISION and ENVISION scenario planner (ESP)

ENVISION and the related ENVISION Scenario Planner (ESP) were developed as research-driven PSS tools through the Co-operative Research Centre for Spatial Information (CRC SI). ENVISION has been designed for use at the subdivision and precinct level and assists governments in identifying greyfield sites for redevelopment (Pettit et al., 2014). Currently, it has road and limited transport data, with the capacity to add new transport and land use layers. Outputs are limited to finding precincts close to specific forms of transport and analyses are done in 2D. The tool is similar in some respects to What If? as it uses a multiple criteria evaluation (MCE) approach to determining suitable land for urban growth. However, its primarily focus is to determine where developer might be targeting future land acquisition through the calculation of a residential potential index (Newton, Newman, Glackin, & Trubka, 2012).

While ENVISION identifies sites for redevelopment, ENVISION Scenario Planner (ESP) provides "visualisation, workflows and assessment at the next scale down" allowing users to understand the impacts of small-scale design features such as building setbacks (Pettit et al., 2014, p. 48). It assesses redevelopment scenarios with 3D analyses and performance assessments (Trubka et al., 2015). The tool contains minimal transport data and instead focuses its strength on housing 'typologies' which are placed into a precinct. Each typology takes significant time to prepare and assess, partially because each is assessed to accommodate region-specific climate factors. ESP was developed as an iterative co-design process, which better reflects the needs of its users with response-driven improvements to the software (Pettit et al., 2014; Trubka et al., 2015).

4.3.2. Application in Melbourne

To guide Melbourne's growth as it swells from 4.5 million to a projected population of almost 8 million in 2050, *Plan Melbourne 2017–2050* was released as a "refresh" of the 2014 *Plan Melbourne* (Victorian Government, 2016). It identifies six national employment and innovation clusters (NEIC) that effectively distribute major activity centres throughout the metropolitan area to reinforce the polycentric nature of the city. These areas include employment hubs but will also become focus areas for absorbing part of the aspirational 70% infill development, which is especially important considering Melbourne's footprint is three times larger than the global average (Newton et al., 2012; Turner & Foran, 2008).

Newton et al. (2012) identified the under-utilisation of Melbourne's middle suburbs, areas 10–30 km from the CBD. ENVISION was used to assist planning efforts in one of the middle suburbs, the City of Manningham. Through workshops, stakeholders used ENVISION's multi-criteria evaluation (MCE) tool to identify significant variables, such as distances to public transit and amenities, and weight them on a scale from 1 to 20, as shown in Fig. 4 (Glackin, 2012). This analysis revealed zones to consider for redevelopment. Some aligned with plans to add density along the main transit corridor, but others were new locations not previously identified in planning documents (Newton et al., 2012).

Newly identified sites were further investigated through data filtering, looking at indicators of residential development potential such as "age of dwelling, condition, size of land, frontage" and areas without potential such as "heritage overlay, strata title" (Newton et al., 2012, p. 153). Potential redevelopment sites are clearly identified in green in

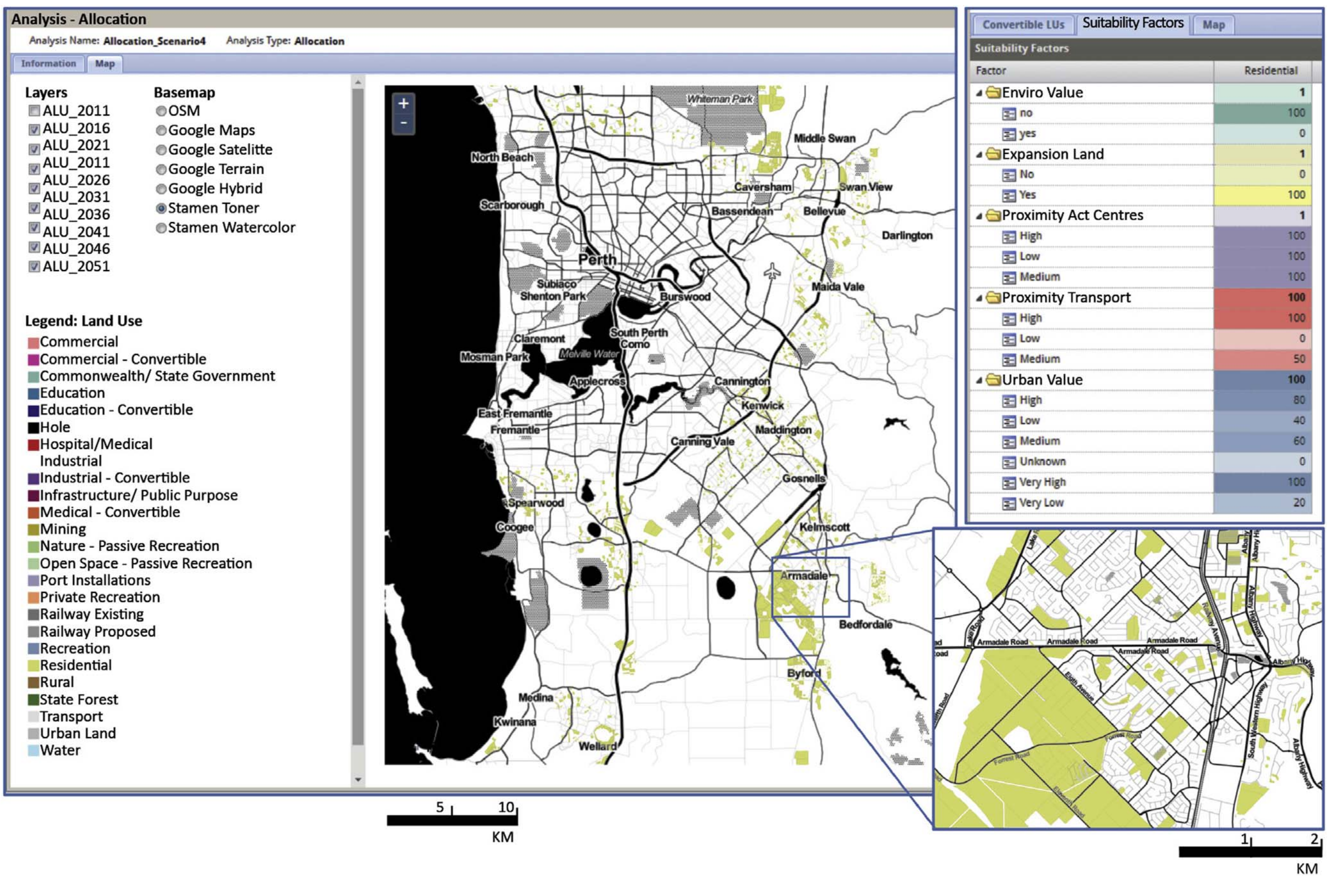

Fig. 3. For each scenario, users rank the importance of different land suitability criteria, and What If? then allocates land uses accordingly. This output shows residential land allocation to 2051.

Fig. 4, and areas with the most contiguous parcels were identified in blue for potential redevelopment in blue.

Throughout other middle suburbs in Melbourne, more detailed analyses occurred with the use of ESP, to conduct a smaller-scale analysis of housing typologies. Trubka et al. (2015) discuss ESP's use at workshops in Melbourne for the Cities of Maroondah, Dandenong, and Yarra, focusing on sustainability outcomes of different housing scenarios. For each of the three study areas, a precinct boundary was defined, road layouts were edited, and land-uses were assigned to all subdivisions (Pettit et al., 2014). The scenario planning process, described in detail by Trubka et al. (2015), involved:

(i) Selecting land-use classes (there are seven: Residential, Commercial, Institutional, Mixed-Use, Open Space, Pathway, and Asset). Residential is the most detailed; it has 110 fields but most are pre-populated.
(ii) Placing typologies on lots within the precinct. The tool calculates a range of outputs including water demand, stormwater runoff, and embodied carbon.
(iii) Editing attributes of each typology. Modelling is therefore very detailed, and reports can be generated for various sub-sets of objects within the precinct.

ESP's capabilities also allowed modelled scenarios to prioritise low-carbon development. For residences, ESP calculated energy demand estimates based on climate zone, orientation, and pre-loaded heating and cooling data. All modelled scenarios were compared to a business-*as*-usual scenario, which was auto-generated by ESP (Trubka et al., 2015). Research from these workshops is being used in ongoing discussions to inform the Melbourne Metropolitan Strategy, as evidenced in a discussion paper (DELWP, 2015; Trubka et al., 2015). In Maroondah, both ENVISION and ESP made a case for greyfield precincts as a critical component of their housing strategy (Maroondah City Council, 2016), discussed further in the Community Engagement Report (Maroondah City Council, 2016a). Monthly community advisory committee meetings provided feedback on scenarios generated by the PSS, allowing for revisions to reflect community interests.

4.4. Subdivision application (Brisbane – CommunityViz®)

4.4.1. CommunityViz®

Developed by the Orton Family Foundation (Rutland, Vermont, USA), CommunityViz® consists of two integrated extensions to ArcGIS: Scenario 360 and Scenario 3D. Scenario 360 extends the quantitative capabilities of ArcGIS by enabling formula-based spreadsheet-like calculations to be performed on geographic data. Formula-based GIS data attributes allow on-the-fly adjustment of numeric and geographic inputs as well as automated recalculation of maps and quantitative output in a process referred to as "dynamic analysis" (Walker & Daniels, 2011, p. 32). Results are presented as a series of maps and linked charts. Scenario 3D allows for three-dimensional display of the built environment and landscape with real-time object manipulation and movement in a semi photo-realistic setting (Lieske & Hamerlinck, 2015). The tool has been applied at the subdivision, precinct and city level. CommunityViz® has been used in a number of North American communities in scenario planning and to develop preferred growth scenarios (Placeways, 2016).

4.4.2. Application in Brisbane

The *Planning Act 2016* (Queensland Government, 2016), is the overarching legislation under which Local Government Authorities (LGAs) operate in Queensland, and one of its main objectives is

Fig. 4. ENVISION's Multi-Criteria Evaluation (MCE) input enables the user to select variables and weight their significance; Based on these criteria, ENVISION then selects land with highest redevelopment potential (green) and identifies parcels that could be consolidated for larger-scale development (blue) (Glackin, 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

preserving and enhancing ecological sustainability. LGAs produce master plans and structure plans that guide redevelopment efforts and align with this legislation. One such plan is the Brisbane City Council's 2006 Proposed Structure Plan for part of the West End, proposing high-rise mixed-use buildings to be placed in a historically low-density area. The plan included a 2D map with proposed building heights and land-uses but only limited impact assessment of the proposed density changes and therefore was met with some concern by community members. The West End Community Association (WECA) sought a way to assess the potential impacts of the plan and to use that information to engage with both the local community and Council (Lieske et al., 2008).

With the goal of facilitating a dialogue between the community and local government around these issues, CommunityViz® was used to develop a scenario-based impact analysis of the structure plan. This consisted of two scenarios, *current conditions* and *proposed structure plan*, based on the different land-use categories in Brisbane. Stakeholder concerns were input as variables using CommunityViz® slider bar technology, as shown in the ‘Assumptions’ menu in Fig. 5. Examples such as maximum building heights and distance to transit were included and different values were experimented with in order to evaluate how changes in threshold values, along with proposed land-use changes, meet the needs of both government and the community. For the proposed structure plan, and all alternate development scenarios, before-and-after land uses were compared on a 2D land use map, as shown in Fig. 5. Before-and-after densities were also compared in a bar graph (also shown in Fig. 5) displaying affordable housing, residences, commercial office, retail, cultural amenities, and open space for each scenario. CommunityViz® also displays these changes on 3D maps and additional charts (such as the percent of each land use shown in Fig. 5) that communicate the impact assessment values.

The results demonstrated that the structure plan will:

- Substantially increase jobs for all land uses (with the exception of cultural which shows only a slight increase)
- Increase affordable housing at a similar rate to overall residential growth
- Significantly increase both daytime and night time populations
- Provide inadequate public transportation to serve the increased population
- Fall short of Brisbane City Council (2008) open space standards

Among the goals of presenting these results publicly was to show how geographic information-based tools could be used to support implementation of the Southeast Queensland Regional Plan, Brisbane City Council planning efforts and West End residents by calculating and showing impacts, displaying results in 2D maps and 3D visualisations, communicating effectively with stakeholders, and providing factual and transparent information to help separate fact from opinion and values. The initial presentation of results was via webinar to the WECA chair and several committee members; WECA was interested in continued involvement with the project and felt the visual component of the results to be particularly important. This process assisted in managing concerns and separating fact from opinion – simply by providing transparent data to show the impacts of land-use changes.

5. Results and discussion

In the vignettes above, we saw how understanding of affordability

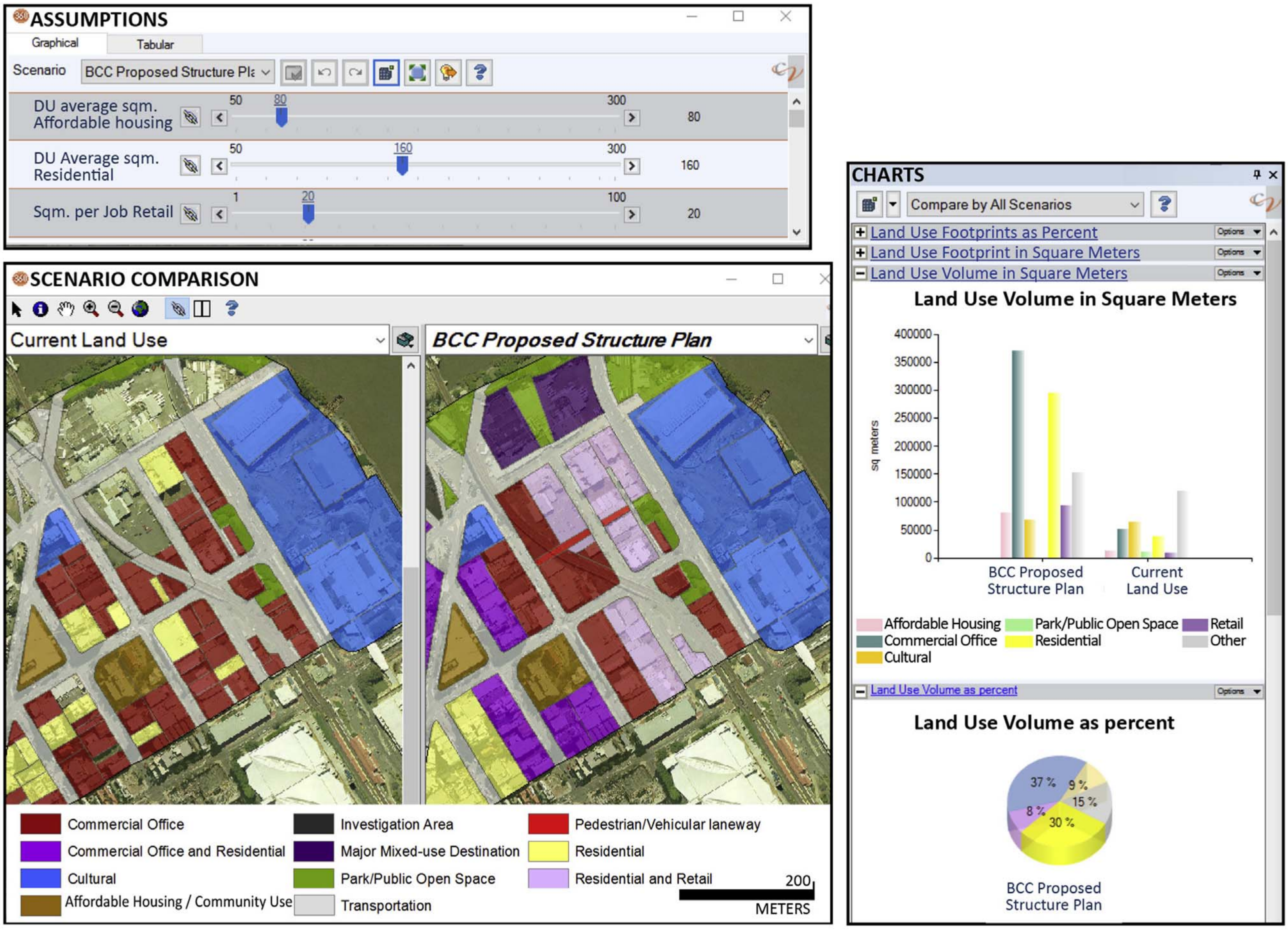

Fig. 5. CommunityViz® slider bars allow users to input assumptions, which are used to generate comparisons between current conditions and proposed changes (shown here in 2D maps and bar graphs).

at a local level can assist in more targeted policy discussions; how ecology can be prioritised along with increased land allocation for employment uses; how the pressure to accommodate urbanisation with sprawl can be avoided by a more informed identification of infill sites; and how visualisation and workshops can be used to facilitate planning discussions amongst stakeholders with different interests. Using a PSS is like designing an experiment: the user must identify a challenge, propose development scenarios that might address it, select variables to 'test' that might indicate success or failure, run the system and explore the results. One of the most exciting opportunities that PSS present is the chance for planners to design these experiments to create new dialogues around complex planning challenges.

The four PSS applications researched in the vignettes were customised to a specific problem domain working closely with the planning agencies involved. Many of these digital tools have been designed with a degree of flexibility which can support a holistic systems approach to decision making.

5.1. Addressing issues preventing mainstream adoption

The vignettes show PSS use in collaborative settings to support group decision making, demonstrating one of their greatest strengths. This helps address the risks of non-compliance with land-use and environmental policy that Waddell (2011) highlights. For instance, by identifying areas for urban infill in Melbourne, CommunityViz® presents a series of options but does not auto-select a development site. This allowed for planners to then critically evaluate each site for policy compliance. Merging processes of digital planning support and critical discussion allow PSS to effectively bring together stakeholders and their concerns, instead of technocratically selecting a site in isolation. However, it is important to note that in all case studies it was the researchers driving the PSS tools in these forums. To this point, PSS presence in education curriculums, identified as an issue by Russo et al. (2017), could assist in empowering planners to become more active in their use and boarder adoption as part of a larger critical analysis of urban challenges. They present the chance to combine previously unrelated data sets to answer questions about interrelationships in cities. The evolution of smart cities related education programs which cover PSS training, such as in courses offered at University College London, Universidad Politécnica de Madrid, and the University of New South Wales, are an important step to address the adoption issue.

The need for increased transparency and reliability in PSS (Russo et al., 2017) is beginning to be addressed, as seen in the above examples. ENVISION and ESP created scenario plans which community groups could then critique for further refinement, and CommunityViz® increased transparency by incorporating variables using slider bars that facilitate discussion about and easy modification of data input values. In the vignettes, What If?, ESP, and CommunityViz® each held workshops with stakeholders to identify the 'key variables' to be tested. Both the inputs and outputs of each PSS were modified based on workshop feedback, and with open source software (as is used by What If? and ESP), even more project-specific alterations can be made of the tools for city planning activities that need additional capabilities. Looking forward, increased transparency can also be achieved with a co-design approach, which is an iterative design process that adapts and edits the tool's software based on feedback from user groups. This approach was used to develop core functions of ESP and to select alterative prototypes for uncertain components (Pettit et al., 2014). There is still room for improvements to participatory approaches in PSS to reflect a more bottom-up development process. Researchers can look to examples of civic hacking as discussed by Townsend (2013) for ways to engage grassroots-level interaction with PSS.

The vignettes also bring clarity to how PSS can involve and deal with big data. Unique data sets are combined in each case study, demonstrating how the *variety* of available data can be used; for instance, the AURIN Portal combined spatial-temporal data on dwelling types with median house price data to product a more fine-grain affordability analysis. Each vignette demonstrates how data's *visualisation* is essential to facilitate understanding and dialogue amongst stakeholders; in addition, each vignette demonstrated the added *value* brought to the planning process with PSS. For instance, PSS allowed Perth to test scenarios that allow economic growth to occur while simultaneously preserving ecological assets.

5.2. Addressing challenges for further development

Moving forward, PSS are challenged to address seemingly conflicting goals. First, they must achieve a balance of complexity and simplicity (Geertman, 2016) by handling a large number of input variables but outputting results in a user-friendly, clear visualisation. Each of the PSS presented above communicated results through dashboards or graphics. The AURIN Portal coloured values on a map, What If? used gradients to indicate land best suitable for residential development, CommunityViz® output clear 2D and 3D before-and-after visualisations to show development impacts, and ENVISION and ESP highlighted areas for infill at the subdivision level making it easy for planners to identify larger clusters of land for development. These were the final visualisations, but even during the analysis process, graphics such as slider bars make it easy to quickly assess impacts of different scenarios. Maintaining and improving visualisation of PSS is key to improving their usability within the planning profession.

Second, there is a need for improved co-ordination between those responsible for PSS adoption and PSS implementation (Vonk & Geertman, 2008). In this area, the vignettes were less successful. Each PSS application was driven by the researchers who have helped develop and implement the tool but are ultimately not responsible for planning decisions. This can also be addressed with increased PSS education and training, increased use of open software by developers working with planning agencies and open data which is required to fuel the PSS described in this paper.

Third, the need to balance creativity and control (Vonk & Geertman, 2008) will be an ongoing test, as PSS tools need to be agile in their deployment and user friendliness for a myriad of end users including planners, policy-makers and citizens. Open data and open source software approaches can also empower civic hacking applications and customization of PSS. Too much top-down control in the development and application of PSS inhibits equitable access to such data driven smart city toolkits. Equity is further impacted by those in control of data sets, which serves as a caution to large private companies and others who wish to restrict access to data inputs and outputs. In relation to data, big data and spatial data not only need to be collected in formats usable for urban analysis (Batty, 2016) but also must be critically assessed to ensure they are used to represent the interests of all segments of the population. Just as big data faces a challenge of moving beyond technology to investigate organisational and political impacts (Batty, 2015), we suggest further research into the impacts and opportunities of PSS adoption on the larger operation of the city. The ability of PSS to engage communities through workshops should be developed even further, allowing development of city plans that represent interests of local groups and continue to focus on bottom-up processes.

6. Conclusion

The use of digital PSS has the capacity to enable sustainable or even regenerative growth in rapidly urbanising areas, but this requires continued improvements to address the challenges confronting their mainstream adoption. Within the context of Australia, the use of PSS supports the pillars of the Smart Cities Plan by leveraging open data driven solutions and conducting robust evaluations of development scenarios to guide smarter policy and infrastructure investment. Globally, smart cities are continually refining their visions, strategies and policies to break down silos, spur innovation and embrace greater ICT connectivity. The PSS tools critically reviewed in this paper enable city planners and policy makers to measure and identify relationships between data inputs and factors and their likely impact on cities. For example: housing prices, travel times, public transit locations, land area, terrain, flood zones, and developer contributions surrounding infrastructure. Although planning practice is becoming more receptive to PSS, the development of more agile PSS tools that can invite easy, inexpensive and collaborative scenario building has not yet happened. However, as governments move towards open data policies and clearer data standards and universities integrate PSS education and training into curriculums, widespread use of PSS could become a reality. The mainstream use of digital PSS has the capacity to enable sustainable or even regenerative growth in rapidly urbanising areas by providing timely evidence bases to assist policy makers in delivering better city planning outcomes. With such tools, the anxiety about future growth in cities can be embraced and resolved into a more hopeful recognition of potential change as we continue to strive for more sustainable, productive, equitable and resilient cities. However, it is essential that citizens and local communities be increasingly engaged in the use of PSS, and this remains a fundamental challenge to 'smart' city planning.

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