# THE INTEGRATION OF CELLULAR AUTOMATA AND WHAT IF? FOR SCENARIO PLANNING: FUTURE RESIDENTIAL EXPANSION IN THE CITY OF IPSWICH

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**ABSTRACT:**

The ever-increasing volumes of available data for urban planning and management have led to the development of a range of planning support systems (PSS) for the design of more flexible and people-oriented cities. In the time of rapid urbanization, there has also been a continued focus on land use change models to simulate its complex dynamics. However, the integration of land use change models with planning support systems has received comparatively little attention, despite its potential to provide a more comprehensive understanding of urban futures over spatial and temporal scales. Considering this, a Cellular Automata (CA) land use change model has been coupled with the What If? PSS in this research. Using the City of Ipswich as the study case, its land use regulations and interaction with surroundings are analysed with multi-source data such as population variation and infrastructure distribution. Land suitability evaluation and demand projections have been modelled using What If? with detailed processes of residential expansion under different scenarios. Two scenarios with different planning strategies are analysed for their future development. The results indicate that continued growth of current residential areas would be the most reasonable strategy for the study area in the following years. By using scenario planning approach, the proposed CA – What If model can be used as a practical tool to analyse the future development of cities. Such data-driven models and tools enable urban planners and policymakers to explore future growth scenarios in the era of big data and global urbanization.

## 1. INTRODUCTION

Urban sprawl, which refers to the growth in urban areas with economic development and population migration, has been widely observed at a global-scale during the past decades (Brueckner, 2000; Couch, Petschel-Held and Leontidou, 2008; Yu and Ng, 2007). According to the 2018 World Urbanization Prospects, 55% of the world's population resides in urban areas, which is almost double the ratio around the middle of the 20th century. It is also projected that there will be a further 18% increase of new urban residents by the end of year 2050 (United Nations, 2018). Nevertheless, the conflict between growing demand for food and decreased agricultural land, which is the main source of newly developed metropolitan areas, becomes an obstacle to this global urbanization trend. In addition, the urbanization process has an impact on climate change (Kalnay and Cai, 2003), deforestation (Grimmond, 2007), loss of biodiversity (González-Orozco et al., 2016) and species richness (McKinney, 2008) since the beginning of the 21st century. Therefore, by exploring the possible urban development under different scenarios, as well as their influences on the earth system at multiple spatial and temporal scales, state government could obtain a better understanding of the interactive mechanism between city, human activities and the surrounding environment. This could be of significant importance for their policy and decision making.

The idea of PSS can be dated back to the 1970s, when Lee Jr (1973) cast doubt on the construction of large-scale urban models. PSSs are geo-information technology-based instruments that are dedicated to support those involved in planning the performance of specific tasks (Geertman, 2006). PSS aim to assist urban planners and policymakers to simulate the expansion of their cities more intuitively and reliably. On the basis of modelling techniques, PSS can be categorized into four groups: large-scale, rule-based, state-change and cellular automata (CA) based (Klosterman and Pettit, 2005). Modern examples that have seen practical use include UrbanSim (Jin and Lee, 2018; Waddell, 2002), What If? (Klosterman, 1999; Pettit et al., 2015), CommunityViz (Kwartler and Bernard, 2001; Walker, 2017) and SLEUTH (Clarke and Gaydos, 1998; Rienow and Goetzke, 2015). Among the suite of available PSSs, What If? has been designed to be a transparent, flexible, and user-friendly system. The What If? PSS comprises land use suitability, land use demand modules with a dedicated allocation procedure for generating holistic land-use planning scenarios (Klosterman, 1999).

Predating the first PSS, scenario planning was initially proposed by Royal Dutch/Shell for the generation and evaluation of its strategic options between the late 1960s and early 1970s (Wack, 1985). With the awareness of urban growth and sustainable development (Naess, 2001), scenario planning has been used to forecast and analyse land use patterns, which is a complex issue that involves negotiations and compromises of various stakeholders (Li and Liu, 2008). It is also taken as a tool to explore and evaluate the extensive uncertainties of possible future developments (Van Vuuren et al., 2012). With the development of its theories, different urban sprawl and development scenarios are produced by PSS to identify the most suitable scheme in different case studies. As a cellular automata

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mechanism-based model, SLEUTH has been used extensively used for scenario planning, with early reported applications in USA: Washington-Baltimore region (Jantz, Goetz and Shelley, 2004), Houston metropolitan area (Oguz, Klein and Srinivasan, 2007), Tulare County, California (Onsted and Clarke, 2011). Afterwards, it was applied to other regions such as Isfahan Metropolitan Area, Iran (Bihamta et al., 2015) and Changzhou, China (Liu et al., 2017). Similarly, CommunityViz has been used to assess the impacts of local policies in Wyoming, USA (Lieske et al., 2003) and Wroclaw, Poland (Kazak, Szewrański and Decewicz, 2013), respectively. Furthermore, additionally scenario case studies with What If? have been reported in different Australian states: sustainable urban-growth scenarios for Hervey Bay in Queensland, 2021 (Pettit, 2005), land-use change scenarios for Mitchell Shire in Victoria, 2031 (C. J. Pettit et al., 2008) and land suitability scenarios of Perth-Peel region in Western Australia, 2031 (Pettit et al., 2015). Generally speaking, the practical value of exploring unknown urban futures has been increasingly accepted by both researchers and planners in practice. However, the majority of PSSs operate on quantitative spatial planning models, which are static in nature and lack causal effects and random disturbances during urban development. Besides, even though PSS contains the module of land use change, it mainly focuses on the allocation and distribution of land parcels in specific planning applications (Geertman and Stillwell, 2004, 2012), rather than the detailed processes of urban land use change, as well as its interactions with spatial variables under different circumstances.

In the field of land use change modelling, researchers have proposed hybrid models and systems by coupling different models to examine a single domain (O'Sullivan et al., 2016). Concerning the afore-mentioned problem, an interval-probabilistic land-use allocation model (IPLAM) has been developed and coupled with different development scenarios, which assisted land managers to obtain insight regarding trade-offs between environmental and economic objectives in land use system of Wuhan City, China (Tan et al., 2017). Meanwhile, Ghavami, Taleai, and Arentze (2017) designed a Multi Agent based Land Use Planning Support system (MALUPS) to simulate the interactions between pre and automated negotiation phrases. It produced a final planning scheme with higher social utility and better spatial land use configurations. However, despite the current success of hybrid models, there are still relatively few outcomes concerning the collaboration between PSS and land use change models, which is expected to promote the normative and goal-oriented strategic planning for future (Couclelis, 2005). To fill this gap, this research proposes a hybrid framework for coupling a PSS with cellular automata, a commonly used land use change modelling approach. The hybrid framework combines top-down (macro-level) requirements of urban system from PSS in an objective and quantitated manner with bottom-up (micro-level) modelling approaches.

This paper is divided into four sections following this introduction: The general workflow of CA – What If model and its implementation, including demand projection, scenario construction and evaluation, are described in Section 2. Taking the City of Ipswich, Australia as the study area, Section 3 contains a case study of the CA – What If model, which provides detailed allocations of urban development demand to specific locations under two different scenarios. The evaluation of scenarios is also elaborated at the end of this Section. Lastly, detailed comparison and analysis on urban development situations under different scenarios, as well as the key findings of this paper, are summarized in Sections 4 and 5.

## 2. METHODOLOGY

The prediction of future land use scenarios is executed in online What If? (OWI), a GIS-based planning support system, which is being made available through the Australian Urban Research Infrastructure Network (AURIN) (Pettit et al., 2020; Pettit et al., 2013). In the current model, every scenario comprises three sub-scenarios: suitability, demand and allocation control. They determine the relative suitability, projected future demands, as well as the control setting of allocation procedures.

### 2.1 Population projection and scenario construction

**2.1.1 Population projection**: The predicted population of specific year $j$ can be estimated using the following equation (Klosterman, 2008; Pettit et al., 2015):

$$P_j = P_i * (1 + R_p)^n, \tag{1}$$

where $n$ = difference between years $i$ and $j$
$R_p$= rate of population growth
$P_j$, $P_i$= population of projected and current (the base year for modelling) years

The parameter $R_p$ can be derived from past trend of residential demand:

$$R_p = \frac{P_{Yi} - P_{Yj}}{Yi - Yj}, \tag{2}$$

where $Yi, Yj$= historical and current years
$P_{yi}$, $P_{yj}$= population of projected and current (the base year for modelling) years

In OWI, the projection of future population is under the assumption that future increase of population will be static and equal to the previous rate.

**2.1.2 Scenario construction**: The scenario is the combination of the three sub-scenarios (C. Pettit et al., 2008):

$$\text{Scenario} = Sce_s \cup Sce_D \cup Sce_{AC}, \tag{3}$$

where $Sce_S$ = land suitability sub-scenario
$Sce_D$ = land demand sub-scenario
$Sce_{AC}$ = allocation control sub-scenario

1. Suitability sub-scenario
The suitability sub-scenario ($Sce_S$) determines the suitability of different parcels with various land uses. Compared with the traditional evaluation procedure, which might take weeks to be completed, the computer-based suitability evaluation is much efficient and objective.

A weighted sum method (Marler and Arora, 2010) has been applied for the computing of suitability:

$$\mathrm{S}_{jk} = f_n \times w_n, \tag{4}$$

where $S_{jk}$ = the suitability score of a specific conversion from land use $j$ to $k$
$f_n$ = driving factor $n$
$W_n$ = weight of driving factor $n$


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With the iteration of evaluation, the appropriateness of land use conversion of each parcel will be identified and classified into five categories: Low, Medium-low, Medium, Medium-high and High.

2. Demand sub-scenario
The Demand sub-scenario ($Sce_D$) takes the population and employment growth projections defined in the Demand Setup, and computes the amount of residential land to accommodate the projected household growth.

In this scenario, the household number of the study area can be estimated by equation (5) (Klosterman, 2008; Pettit et al., 2015):

$$H_j = H_i * (1 + R_h)^n, \tag{5}$$

where $H_j$ and $H_i$ = the number of households in projected and current years
$n$ = time gap between projected and current years
$R_h$ = rate of household growth

Similar to population growth rate, $R_h$ is determined by the past residential data from Demand Setup:

$$R_h = \frac{H_{y1} - H_{y2}}{Y1 - Y2}, \tag{6}$$

where $H_{y1}$ and $H_{y2}$ = the total number of households in historical years *y1* and *y2*

Besides, the estimated demand of residential land $Demand_{resi}$ can be calculated as:

$$Demand_{resi} = \sum_i \frac{B_i \times (1 - IR_i)\left(\frac{P_f}{(1 - VR_i)}\right) * Count_i}{Den_f}, \tag{7}$$

where $i$ = particular type of residential housing
$B_i$ = future breakdown percentage
$IR_i$ = future infill rate
$VR_i$ = particular type of residential housing
$P_f$ = the predicted future population
$Count_i$ = total number of residential housing *i* in current year
$Den_f$ = future density of residential housing *i*

3. Allocation control sub-scenario
The Allocation control sub-scenario ($Sce_{AC}$) administers the newly developed residential land by taking infrastructure, land use planning and growth patterns into consideration. Specifically, $Sce_{AC}$ judges whether 1) the parcel has public transport service infrastructure and 2) planned land use can be allocated with new residential demand.

$$Parcel_i = \begin{cases} 1, Satisfied \\ 0, Not\ satisified \end{cases}, \tag{8}$$

In short, any parcel *i* (*i* ≤ total number of parcels within the study area) can be developed as new residential if it satisfied one of the following conditions: 1) Have corresponding public transport service infrastructure/Residential is considered as one of the planned land uses; 2) No allocation control is compulsory in this sub-scenario.

After the combination of above-mentioned sub-scenarios, the land use demand in Demand scenario will be allocated to different locations at parcel-level scale. The allocation procedure is based on 1) their relative suitability as user defined in the suitability sub-scenario, and 2) the allocation controls in the allocation control sub-scenario.

### 2.2 CA-based allocation process

Afterwards, CA model will allocate projected demand according to the result of suitability evaluation. CA model is a discrete model with several applications in the simulation of land use change and urban expansion (Chaudhuri and Clarke, 2013). The transfer probability of $cell_{ij}$ is described as (Li et al., 2007):

$$P_{ij}^t = P_c \times \Omega_{ij}^t \times con_{ij}^t \times Rand, \tag{9}$$

where $P_{ij}^t$ = transfer probability of $Cell_{ij}$
$P_c$ = suitability of its current location (which derived from constructed scenario)
$\Omega_{ij}^t$ = neighbourhood configuration
$con_{ij}^t$ = the constrict of cell transformation in its current location
$Rand$ = the stochastic perturbation during real land use transformation

The allocation process is composed of multiple iterations, and each iteration is in accordance with one month in reality. Specifically, every iteration can be summarized with three key steps: Initially, the transfer suitability will be calculated using equation (9) and all candidate cells are ranked in descending order. Afterwards, the non-residential parcels with higher probabilities will be transformed as residential in the current iteration until the sum area of selected parcels reaches the pre-defined threshold. The threshold refers to the ratio of land use demand and iteration number. The third step is to update the residential and non-residential layers, recalculate the values of corresponding driving factors, and continue the allocation process in the next iteration

### 2.3 Scenario evaluations

Two indices for scenario evaluation have been proposed in this section.
1. Mean patch size
Mean patch size (MPS) equals to the total area of specific land use divided by the number of patches (Li and Archer, 1997), which can be calculated as:

$$MPS_i = \frac{A_i}{Num_i}, \tag{10}$$

where $A_i$ = the sum area of patches in land use *i*
$Num_i$ = the total number of patches in land use *i*

By comparing the MPS values in 2016 (real data) and 2031 (simulated scenario), the variability of patch (parcel) sizes can be identified.

2. Interquartile range
As an indicator of descriptive statistics, interquartile range (IQR) is the difference of 3rd and 1st quartile (Q3 and Q1), namely the medians of second and first half of data samples (Upton and Cook, 1996).

$$IQR = Q3 - Q1, \tag{11}$$

where $Q3$ = the median of second half of data sample
$Q1$ = the median of first half of data sample


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In comparison with MPS, IQR measures the spread of the value range around the median value, which could exclude the influence from outliers.

## 3. CASE STUDY

### 3.1 Study area and data source

The City of Ipswich is a Local Government Area (LGA) in the South East Queensland (SEQ) region, Australia (Figure 1). In the most recent census of population and housing there were 50,060 households in Ipswich, with a total population of 193,773 (ABS, 2016). As one of the satellite towns for the greater Brisbane region, a series of land use transformation has been observed in Ipswich during the past decades (Lu, Laffan and Pettit, 2022). Besides, Ipswich will accommodate the proportions of expansion growth in South East Queensland (SEQ) region (Queensland Government, 2017a), and thus the population of Ipswich is projected to double by 2031 (Ipswich City Council, 2015). Considering the continuous growth of population and increasing demand for residential land, the City of Ipswich has been identified as an ideal place for the proposed research.

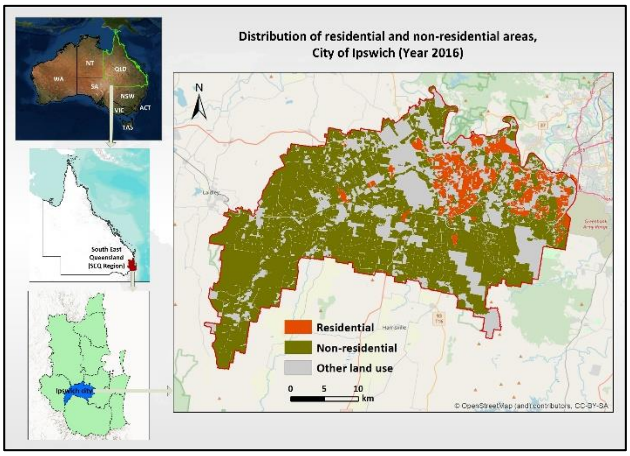



**Figure 1**. Location of City of Ipswich.

### 3.2 Future scenarios of Ipswich

**3.2.1 Suitability sub-scenario**: In the suitability sub-scenario, the driving factors are mainly derived from datasets sourced from the Australian Bureau of Statistics (ABS) and Queensland Spatial Catalogue (QSpatial), the open-data platform of Queensland Government. The specific factors and detailed categories are determined on the basis of previous What If study case (Pettit et al., 2015) and data availability. Firstly, activity centre accessibility (F_Actcen) can be classified into two categories, parcels within 1000 m of commercial meshblocks (the smallest census unit of ABS) near Central Ipswich are regarded as "Near district centre"; while the remaining ones are tagged as "None". Similarly, the thresholds of Education accessibility (F_Edu), Environment value (F_Envirvalue), Public transport accessibility (F_Pubacc) and Slope (F_Slope) are listed in Table 2. In addition, the priority areas of Urban expansion (F_Urbanexp) are identified according to the South East Queensland Regional Plan (2009-2031), as a reflection of the designed planning scheme.

| Factors | Data source |
|---|---|
| F_Actcen | Land use map 2016 - QSpatial |
| F_Edu | Education meshblock - ABS |
| F_Envirvalue | Protected areas - QSpatial |
| F_Slope | Digital elevation model - QSpatial |
| F_Urbanexp | Development areas - South East Queensland Regional Plan 2009 - 2031 |
| F_Pubacc | Railway stations and sidings - QSpatial |

**Table 1**. Selected factors and data source.

**3.2.2 Demand sub-scenario**: The demographic trends in the City of Ipswich can be obtained from historical census results (Table 2). The future population in demand sub-scenario is projected with a static population growth assumption, namely population and vacancy rate will be stable according to the past and current demographic trends. Accordingly, OWI makes a projection of 1,113.93 ha of residential land use demand from 2016 to 2031.

| | Year 2006 | Year 2011 | Year 2016 |
|---|---|---|---|
| Total Population (People) | 140,181 | 166,904 | 193,733 |
| Housing Units | 53,320 | 60,935 | 68,674 |
| Households | 47,568 | 56,327 | 63,656 |
| Vacancy Rate | 7.0% | 7.6% | 7.3% |

**Table 2**. Demographic trends in Ipswich.

**3.2.3 Allocation control sub-scenario**: In this case study, two growth patterns have been established: (1) Residential sprawl, and (2) Growth along transport corridors. In the "Residential sprawl" pattern, candidate parcels near the existing residential areas in 2016 are more likely to be transformed into residential. Similarly, parcels near main roads have more chance to be transformed in the "Growth along transport corridors" pattern.

**3.2.4 Combined scenarios of future Ipswich development**: In order to validate the proposed scenarios equally, suitability factors are applied to provide identical standards. The detailed parameters of suitability and allocation control sub-scenarios are summarized in Table 3.

| Combined scenario | Suitability sub-scenario | | | Allocation sub-control scenario |
|---|---|---|---|---|
| | Factor | Weight | Type | |
| Scenario 1 | F_Actcen | 100 | Near activity centre (80)<br>None (30) | Priority allocation near current residential area of year 2016 (less than 800 m) |
| | F_Edu | 80 | High (85)<br>Medium (50)<br>Low (30) | |
| | F_Envirvalue | 50 | Yes (0)<br>No (50) | |
| | F_Slope | 50 | High suitability (80)<br>Medium suitability (40)<br>Low suitability (10) | |

| | | | | |
|---|---|---|---|---|
| | F_Urban exp | 100 | Priority expansion (95) Ordinary expansion (50) | |
| | F_Pubacc | 80 | High (80) Medium (55) Low (30) | |
| Scenario 2 | F_Actcen | 80 | Near activity centre (65) None (10) | Priority allocation along transport corridors (less than 1000 m) |
| | F_Edu | 70 | High (75) Medium (45) Low (25) | |
| | F_Envirv alue | 60 | Yes (0) No (50) | |
| | F_Slope | 40 | High suitability (80) Medium suitability (40) Low suitability (10) | |
| | F_Urban exp | 90 | Priority expansion (90) Ordinary expansion (40) | |
| | F_Pubacc | 60 | High (65) Medium (35) Low (15) | |

* The numbers indicate the weights of corresponding suitability factors

**Table 3**. Parameters of constructed scenarios.

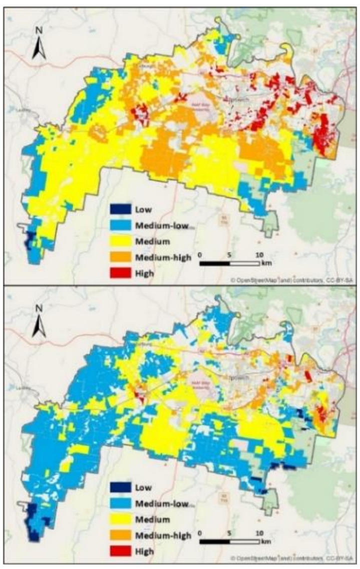



**Figure 2**. Suitability maps of scenario residential development.

### 3.3 Land use allocation by CA models

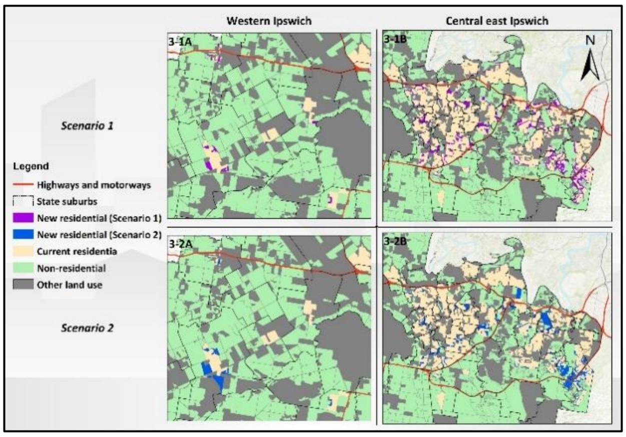



**Figure 3**. Predicted scenario developments of newly residential areas (Year 2016 - 2031).

As Figure 3 indicates, further extension of current residential areas (Year 2016) has been produced by CA – What If model, as the main trend in the City of Ipswich regardless of the difference between scenarios. Therefore, the majority (93.61% in Scenario 1, 93.65% in Scenario 2) of newly transformed residential cells are located in the Central East part of Ipswich (Figures 3-1B and 3-2B), while the remaining 6.39% and 6.35% scattered residential cells are situated in Western Ipswich. Specifically, the new residential cells of Scenario 1, which have been observed in 46 suburbs of Ipswich, are more dispersed compared with the 43 suburbs in Scenario 2.

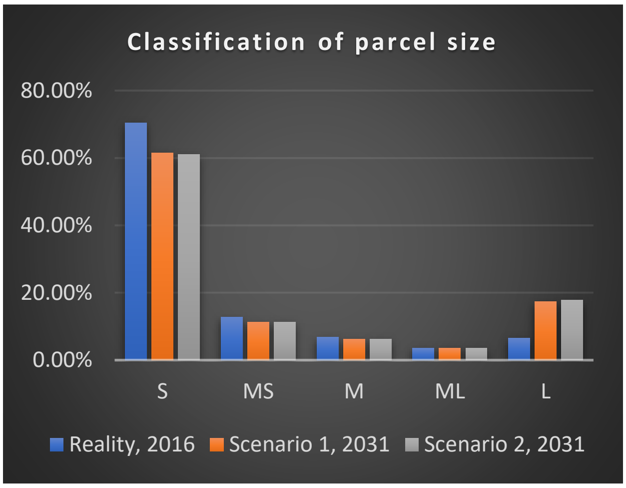
### 3.4 Evaluation of scenario developments

By combining the newly converted residential parcels (Years 2016 - 2031) with the current residential area (Year 2016), the mean value and standard deviation of patch size have been calculated below.

| | Mean patch size (MPS, $m^2$) | Interquartile range (IQR) |
|---|---|---|
| Reality (2016) | 1,028.98 | 320.54 |
| Scenario 1 (2031) | 1,427.66 | 360.38 |
| Scenario 2 (2031) | 1,449.93 | 365.03 |

**Table 4**. Mean value and standard deviation of patch size.

Table 4 illustrates the general characteristics of parcel size of all residential land at the beginning (Year 2016) and end (Year 2031) of simulation period. In order to analyse the range of parcel sizes, they have been classified into five levels based on area extent: small(S) [0, 0.25), medium-small (MS) [0.25, 0.5), medium (M) [0.5, 0.75), medium-large (ML) [0.75, 1) and large (L) (higher than 1) (Unit: ha). The detailed statistics of parcel classification is recorded in Figure 4.




* S: Small, MS: Median-small, M: Medium, ML: Medium-large, L: Large

**Figure 4**. Classification of parcel size (by area).

## 4. DISCUSSION

Concerning the MPS and IQR, there is an obvious difference in parcels between the years 2016 (reality) and 2031 (prediction), but the values for the two scenarios (year 2031) are similar. Specifically, the MPS was 1,028.98 $m^2$ in year 2016, which has increased by 38.75% and 40.91% in scenarios 1 and 2 at the end of prediction period, respectively. Nevertheless, no obvious increment in median patch sizes and IQR have been detected during the same period. Therefore, it is revealed by MPS and IQR that larger parcels are more likely to be selected for residential development during the years 2016 to 2031. As SEQ Regional Plan 2009 - 2031 indicates (Queensland Government, 2017b), Ipswich's population will be two times larger than present, where higher density housing need to be developed in more established urban areas. Considering this, it is anticipated that more residential communities with higher floor space ratio (FAR) and additional public facilities are likely to be built, which could better accommodate the upcoming residents since detached dwellings represent low-density and high-rise apartment buildings are associated with high-density population (Sivam, Karuppannan and Davis, 2012).

The transformation of dwelling types can be also explained by the variation of parcel classes (by area). Although parcel with small size is still the dominant category in both years 2016 and 2031, its ratio has decreased from 70.41% to 61.56% (Scenario 1) and 61.02% (Scenario 2). This downward trend is observed for the ratio of medium-small parcels as well, but relatively inconspicuous compared with variation in small parcels. On the opposite, the ratio of large parcels (areas more than 1 ha) has been predicted to increase by 10.79% and 11.30% in these scenarios. Besides, ratios of medium and medium-large parcels are relatively stable during the simulation period. Overall speaking, the varying ratios of small, medium-small and large parcel categories has further confirmed the switch of transformed parcels in future Ipswich. Additionally, the steady ratios of medium and medium-large parcels imply that the construction of medium-size residential blocks will be continued in the City of Ipswich, but not as much as high-density residential communities.

## 5. CONCLUSION

In this research, an integrated CA – What If model has been proposed and applied to a case study in the City of Ipswich, SEQ Region, Australia. Based on overall land use demand during the years 2016 and 2031, detailed allocation schemes under two potential urban development scenarios are projected at monthly intervals and parcel-level spatial scale. The evaluation of land allocation schemes has been executed by taking both historical data and SEQ Regional Plan 2009 - 2031 into consideration.

It is anticipated that around 1,113.93 ha of residential land is required according to the generated urban growth scenarios of the What If? PSS, where central and eastern Ipswich will be the continuous growth of residential areas. In comparison, the predicted MPS and IQR values of scenario 1 have a closer match to the distribution of residential area in year 2016. Overall, the strategy of Scenario 1, which provides more dwellings by both extended residential areas and increased floor space ratio in suburbs, is more consistent with both historical land use patterns and the decisions of Ipswich City Council.

Overall speaking, it is confirmed that the integrated CA – What If model can be applied for land use demand prediction and allocation simulation. It works as a refined tool for a more comprehensive understanding of the non-linear, unstable and uncertain world (de Roo, 2018). Concerning the emergence of open government data supporting more open and transparent city planning (Hawken, Han and Pettit, 2020), it is also expected that additional factors on human activities and their interactions with cities' spatial structure (Schläpfer et al., 2014; Zhong et al., 2017) will be available for future land use and urban growth modelling. In conclusion, the availability of richer data will ultimately support more detailed and complex scenario analysis, such as the dynamically varying importance of driving factors, for future urban development conducted by urban planners and policymakers.

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