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A panel error correction approach to explore spatial correlation patterns of the dominant housing market in Australian capital cities

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Abstract

Purpose – A panel error correction model has been developed to investigate the spatial correlation patterns among house prices. This paper aims to identify a dominant housing market in the ripple down process.

Design/methodology/approach – Seemingly unrelated regression estimators are adapted to deal with the contemporary correlations and heterogeneity across cities. Impulse response functions are subsequently implemented to simulate the spatial correlation patterns. The newly developed approach is then applied to the Australian capital city house price indices.

Findings – The results suggest that Melbourne should be recognised as the dominant housing market. Four levels were classified within the Australian house price interconnections, namely: Melbourne; Adelaide, Canberra, Perth and Sydney; Brisbane and Hobart; and Darwin.

Originality/value – This research develops a panel regression framework in addressing the spatial correlation patterns of house prices across cities. The ripple-down process of house price dynamics across cities was explored by capturing both the contemporary correlations and heterogeneity, and by identifying the dominant housing market.

Keywords Panel regression, Dominant housing market, Spatial correlation patterns, House price indices, Housing, Australia

Paper type Research paper

1. Introduction

Regional house prices have attracted a lot of attention from researchers in the areas of real estate and regional economics. Regional distinctions and interconnections of house prices appear important for both policy makers and investors. Meen (1996) argued that housing markets may be better characterised as a series of interconnected sub-national markets, indicating that house prices in one region depend on house prices in other regions. This interconnected relationship between regional house prices is known as spatial autocorrelation (Odlund, 1988). Spatial autocorrelations were first raised in the UK’s regional house price studies in the early 1990s. MacDonald and Taylor (1993) tried to address three major issues, namely the segmentation of house prices, the long-run equilibrium and the short-run dynamics of house prices across different regions in Britain. Although the literature was limited, particularly in statistical results, it demonstrated an approach to analyse the spatial autocorrelation in regional house prices. Clapp and Tirtiroglu (1994) tested the significance of a positive feedback hypothesis in Hartford, Connecticut. The study confirmed regional housing markets were not only affected by the historical movements in each individual markets but also by the movements in neighbouring markets.

A specific phenomenon, starting in a particular geographic area, spreading over space and time is defined as spatial diffusion in the regional study area (Morrill et al., 1988). Spatial diffusion describes a process where dynamics in the observation of interest in one area are caused by earlier behaviours in another area. The notation of spatial diffusion patterns of regional house prices describes the process of change in the house prices in a region ripple down to other regions, which is also known as “ripple effects”. The nature of the spatial diffusion patterns of house prices was explained by Meen (1999). It was argued that the immobility of houses leads to the distinctions of house prices in different regions. However, house prices in different regions are interconnected because of migrations, equity transfers, spatial arbitrages, and spatial pattern in the determinants of house prices. Meen also demonstrated the market composition model with applied spatial coefficient heterogeneity in order to capture the structural differences in regional housing markets. The house price diffusion patterns were also demonstrated by previous studies in other countries. For example, a vector autoregressive (VAR) model was applied to examine the diffusion patterns of regional house prices in the Republic of Ireland and Northern Ireland (Stevenson, 2004). In the same study, an asymmetric adjustment was constructed by employing the Heaviside indicator function to partition price differentials of a pair of regional house prices. The results confirmed the Dublin housing market was viewed as the centre, with the effects
spreading to the housing markets in other regions of Ireland. Another study advocated an approach to investigating the pair-wise long-run equilibrium in the housing markets in Australian capital cities, based on the frameworks of the two-stage Engle-Granger cointegration test (Luo et al., 2007). The results confirmed pair-wise long-run equilibrium existed in some pairs of the Australian urban house prices. Liu et al. (2008) employed a VAR model and impulse response function to investigate spatial diffusion patterns of the housing market in Australian capital cities. It was demonstrated that the two biggest cities of Australia, Sydney and Melbourne, had the most stable housing markets with the markets in Adelaide, Brisbane and Canberra being relatively sensitive to the influences from others.

Since spatial autocorrelation exists in regional house prices, the studies based on time-series regression methods ignore the heterogeneity and space-correlated characteristics of house prices. In order to deal with regional heterogeneity, Case et al. (2001) imputed a panel regression to investigated the link between increase in housing, financial wealth and consumer spending. The results confirmed significant effects of housing on consumer spending. The panel regression models were also applied in other studies into the associations between housing dynamics and economic factors across regions, such as gross productivities (Miller et al., 2011a, b). Although these studies depicted the relationships between housing and other economic behaviours across regions, they failed to reflect the spatial correlation between housing markets. Holmes (2007) proposed an innovative approach to investigate the price ratio convergence by employing a seemingly unrelated regression (SUR) unit root test. The SUR unit root test could take into account of heterogeneity in house prices in different regions in the UK, and therefore provided more reliable results than the univariate unit root tests. In further research, Holmes and Grimes (2008) incorporated the theory of first principal component with the SUR unit root test to identify the house price differentials in the UK. The results confirmed that constant long run price ratio convergence existed in all regions in the UK. Tsolacos et al. (2009) built a panel regression model to examine the variation of retail yields in eight Asia-Pacific centres, indicating the advantage of panel regression in studying market dynamics across cities. Ma and Liu (2010) also proposed a panel regression approach to decompose urban house prices into three categories, including regional factors, own-market factors and neighbourhood market factors. Holly et al. (2010) introduced a panel regression method to investigate house price changes across several American states. The study demonstrated house price changes were highly spatially correlated across the observed American states. In comparison, Karaganis (2011) proposed seasonal and spatial house price indices in Greece. In addition to the significant seasonal effects, positive and significant spatial effects were also. The spatial effects on housing investments and economic growth were emphasised by employing a dynamic panel regression approach (Benos et al., 2011).

King (1984) outlined a theory of central place, introducing a hierarchical manner in spatial diffusion. King argued that a phenomenon may emerge in the largest city first, then spreads to the second largest city, and so on. Haynes and Fotheringham(1984) also argued that spatial interconnections were stronger between cities with larger population, but weaker between cities with smaller population. However, the notation of a dominant housing market or hierarchical patterns was neglected by most previous studies into house price spatial autocorrelation. Most previous studies into house price spatial diffusion patterns failed to answer which city should be viewed a dominant role in the process of house price dynamic spreading. Shi et al. (2009) identified the dominant city of spatial diffusion patterns across New Zealand cities, by carrying out Granger causality tests based on a framework of vector error correction model. A series of pair-wise Granger causality tests was carried out to identify a dominant city in each of the three regions in New Zealand. The results confirmed a movement in the house prices in a city could not spread out nationally. This induced spatial diffusion patterns of house price in New Zealand could be caused by internal economic factors in an individual region rather than by migration or spatial arbitrage across regions.

This current research investigated spatial autocorrelation of house prices in the Australian capital cities. A dominant housing market was also identified by applying two-stage Engle-Granger test and VAR Granger causality tests. A panel error correction model was developed to illustrate the temporal and spatial co-movements of house prices. Moreover, impulse response functions based on the estimated were further implemented to depict the spatial diffusion patterns of a shock occurring in the house prices in the dominant housing market. The remains of this paper are organised as follows: Section 2 outlines the criteria of identifying dominant housing markets in Australian capital cities. Section 3 introduces methodologies of penal error correction models and impulse response functions. Section 4 estimates and evaluates the panel error correction model based on the house prices in Australian capital cities. Section 5 simulates the spatial diffusion patterns of the house price shock in the dominant housing market, by using impulse response functions based on the panel error correction model. Section 6 summarises the findings and concludes.

2. Dominant housing market in Australian capital cities

2
Spatial diffusion patterns reflect how a movement in house prices spreads from one city to another over the time. In order to determine a dominant housing market, this research proposes two criteria conditions. First, house prices in a dominant housing market can be expected to have long-run equilibrium or cointegration relationships with house prices in other cities. Second, the house price movements in a dominant housing market are also expected to be stable and significantly impact on the house price movements in other cities. In other words, the housing market in a dominant housing market cannot be influenced by the house price movements in other cities; however a shock house price shock in a dominant housing market can influence in the house price movements in other cities. In the context of a dominant housing market, this section explains the criteria and methods of identifying and applying this the housing markets in Australian capital cities.

2.1 House price levels in Australian capital cities
This research applied the two-stage Engle-Granger and Granger causality test to the house price indices (HPI) in the Australian capital cities. The HPI of the eight state capital cities of Australia were collected from the publications of the Australian Bureau of Statistics (ABS, 2011). The observation period was from the December quarter of 1989 to the June quarter of 2010. The ABS indices are established quarterly and this research makes reference to the 1989-1990 financial year, although the reference became based on the 2003-2004 financial year after the September quarter of 2005 (ABS, 2005). In order to maintain consistency, the HPI established based on the later reference level was convert to the previous reference level, using HPI\textsubscript{1989-90} = w x HPI\textsubscript{2003-04}, where HPI\textsubscript{1989-90} denotes the HPI on the base 1989-1990, HPI\textsubscript{2003-04} denotes the HPI on the base 2003-2004, and w is the converting factor. Table I reports a five-year and overall growth rates, as well as the means and standard deviations of the HPI in the eight capital cities over the observed period.

House price levels in Australian capital cities continued to increase over the observation period, except for a slight decrease in Melbourne in the first five years. Over the last two decades, house price levels in the Australian capital cities has increased by from the lowest at 199.63 per cent in Hobart, to the highest at 470.65 per cent in Darwin. The house price levels increased slowly between 1989 and 2000. Following this house price levels commenced to increase with high growth rates. In the last five years, the speed of house price level increases slowed in all Australian capital cities, which was potentially caused by the emergence of the global financial crisis. As observed in Table I, house price levels in Darwin maintained a fast increase over the last two decades, while house price levels in Sydney increased smoothly.

The means show the average levels of house prices in the eight capital cities, while the standard deviations indicate the volatile nature of the house price levels over the observation period. The house price in Darwin has the highest average level and volatility; the house price in Hobart, on the other hand, has the lowest average level and volatility. The house price level in Sydney appears lower and less volatile than the majority of the capital cities, while the average level and volatility of house price in Melbourne are ranked in middle. It is also interesting to note that house prices in Canberra have a high average level but a low volatility. Since distributions of the house prices are quite different from one city to another, a geographically diversified portfolio may benefit real estate investors. Therefore, it is important to identify the spatial correlation patterns between house prices across the cities.

<table>
<thead>
<tr>
<th></th>
<th>Adelaide</th>
<th>Brisbane</th>
<th>Canberra</th>
<th>Darwin</th>
<th>Hobart</th>
<th>Melbourne</th>
<th>Perth</th>
<th>Sydney</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995-2000 (%)</td>
<td>14.12</td>
<td>4.79</td>
<td>10.85</td>
<td>9.02</td>
<td>3.15</td>
<td>53.75</td>
<td>38.11</td>
<td>36.93</td>
</tr>
<tr>
<td>2000-2005 (%)</td>
<td>88.68</td>
<td>104.38</td>
<td>77.73</td>
<td>50.72</td>
<td>50.06</td>
<td>61.83</td>
<td>83.22</td>
<td>58.97</td>
</tr>
<tr>
<td>2005-2010 (%)</td>
<td>54.27</td>
<td>46.26</td>
<td>51.20</td>
<td>81.67</td>
<td>46.26</td>
<td>73.40</td>
<td>70.94</td>
<td>29.20</td>
</tr>
<tr>
<td>Overall growth (%)</td>
<td>364.96</td>
<td>330.70</td>
<td>296.69</td>
<td>470.65</td>
<td>196.63</td>
<td>322.76</td>
<td>303.14</td>
<td>228.29</td>
</tr>
<tr>
<td>Mean</td>
<td>174.2</td>
<td>210.99</td>
<td>189.32</td>
<td>243.5</td>
<td>160.50</td>
<td>181.81</td>
<td>186.30</td>
<td>178.16</td>
</tr>
<tr>
<td>SD</td>
<td>83.31</td>
<td>100.85</td>
<td>80.23</td>
<td>119.14</td>
<td>56.95</td>
<td>90.65</td>
<td>106.65</td>
<td>70.57</td>
</tr>
</tbody>
</table>

2.2 Identifying long-run equilibrium relationships between housing markets
A two-stage Engle-Granger cointegration test is adapted to investigate whether a stationary long-run equilibrium exists between the house prices (Engle and Granger, 1987). This test is expressed as follows:

\[
p_t = \alpha + \beta_1 p_{t-1} + \mu_{t},
\]
and:

$$\Delta \mu_{ij,t} = c_i + \rho_{ij} \mu_{ij,t-1} + \sum \delta_{ij,t-1} \Delta \mu_{ij,t-1} + \delta_{ij}$$  

(2)

$a_i$ and $b_i$ are estimated long-run parameters between house prices in cities $i$ and $j$, series $\mu_{ij,t}$ is the estimated error terms, and the term $Dm_{ij,t}$ in equation (2) is the first difference of $m_{ij,t}$ in equation (1). A significant non-zero parameter $r_i$ indicates house prices in cities $i$ and $j$ are cointegrated with each other.

The long-run equilibrium relationships between house price levels in each pair of Australian capital cities was established by equation (1); and then equation (2) was used to investigate whether the established equilibrium relationships exist. Table II reports the cointegration relationships between house prices in each pair of the Australian capital cities.

Long-run equilibrium relationships between house price levels were observed in most pairs of Australian capital cities. The HPI in Brisbane, Darwin, Melbourne and Perth were cointegrated with all the other cities in the long-run. The HPI in Darwin moved together with the HPI in all the other cities in the long-run, suggesting its relatively outlying location should not isolate its house price movements from the others. However, the cointegrated relationships did not transit among the house prices in the Australian capital cities. For example, no cointegrated relationship was observed in the house prices in Adelaide and Sydney, although the house prices in those two cities were cointegrated with the house prices in Melbourne. This suggests that Melbourne provides a stochastic common trend for the long-run house price movements in Sydney and Adelaide.

Although the individual differences between Melbourne and Sydney or Adelaide elapsed or moved to a constant over time, the house prices in Sydney and Adelaide could not converge to each other. A similar situation was also found in the house price in Perth. Taking into consideration these long-run relationships with the house prices in other cities, Melbourne and Perth will be potentially selected as dominant cities.

Table II. Pair-wise cointegration relationships

<table>
<thead>
<tr>
<th>Adelaide</th>
<th>Brisbane</th>
<th>Canberra</th>
<th>Darwin</th>
<th>Hobart</th>
<th>Melbourne</th>
<th>Perth</th>
<th>Sydney</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adelaide</td>
<td>NA</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Brisbane</td>
<td>Yes</td>
<td>NA</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Canberra</td>
<td>Yes</td>
<td>Yes</td>
<td>NA</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Darwin</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>NA</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Hobart</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>NA</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Melbourne</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>NA</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Perth</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>NA</td>
</tr>
<tr>
<td>Sydney</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>NA</td>
</tr>
</tbody>
</table>

2.3 Identifying short-run influences between housing markets

A Granger causality test based on the framework of a VAR model is employed to investigate the influence of house price coefficients on each other in a pair of cities (Granger, 1969). The test is expressed as follows:

$$\Delta \theta_j = \lambda_{\theta_j} + \sum_{j=0}^{N} \int \theta_{ij} \Delta \theta_{ij,t-1} + \sum_{j=0}^{N} \int \theta_{ij} \Delta \theta_{ij,t-2} + \cdots + \sum_{j=0}^{N} \int \theta_{ij} \Delta \theta_{ij,t-r} + \omega_t$$  

(3)

Parameter $\theta_{ij,t}$ is the coefficient of the short-run relationship between house price movements in city $i$ and its previous movements or in city $j$. The subscript $r$ indicates the number of temporal lags. If there is at least one parameter $\theta_{ij,t}$ significantly different from zero, the house price movements in city $i$ are Granger caused by the movements in city $j$. Otherwise, the house price movements in city $i$ cannot be Granger caused by the movements in city $j$.

In addition to having long-run equilibrium relationships with house prices in other cities, house prices in a dominant city should also have significant impacts on the housing markets in other cities. Vector Granger causality tests were then applied to house prices in Australian capital cities. The results of the tests are shown in Table III.

A movement in the HPI in Melbourne and Canberra can influence house price movements in three capital cities; movements occurring in Adelaide, Brisbane, Hobart and Sydney can cause influence two capital cities; a
house price movement in Perth can only influence one capital city, Canberra; movements in house prices in Darwin cannot significantly influence house prices in any capital cities. Although house price movements in both Melbourne and Canberra could affect house prices in relatively more capital cities, the house price movements in Melbourne were influenced by fewer capital cities than the house price movements in Canberra.

The results of the Engle-Granger test confirmed HPI in Melbourne is cointegrated with the HPI in all other Australian capital cities. In addition, Granger causality tests demonstrated the house price movement in Melbourne could influence relatively more capital cities; however it could not be influenced by others capital cities. Therefore, Melbourne is identified as the dominant housing market among the Australian capital cities. Based on this finding, a panel error correction model and impulse response functions are established to explore the spatial autocorrelation in house prices in Australian capital cities.

Table III. Granger causality tests for HPI in the Australian cities

<table>
<thead>
<tr>
<th></th>
<th>Adelaide</th>
<th>Brisbane</th>
<th>Canberra</th>
<th>Darwin</th>
<th>Hobart</th>
<th>Melbourne</th>
<th>Perth</th>
<th>Sydney</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adelaide</td>
<td>–</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>*</td>
<td>No</td>
<td>No</td>
<td>–</td>
</tr>
<tr>
<td>Brisbane</td>
<td>No</td>
<td>–</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>**</td>
<td>No</td>
</tr>
<tr>
<td>Canberra</td>
<td>–</td>
<td>**</td>
<td>–</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>**</td>
<td>No</td>
</tr>
<tr>
<td>Darwin</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>–</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Hobart</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>–</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Melbourne</td>
<td>**</td>
<td>No</td>
<td>*</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>–</td>
</tr>
<tr>
<td>Perth</td>
<td>No</td>
<td>No</td>
<td>*</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>–</td>
</tr>
<tr>
<td>Sydney</td>
<td>*</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>–</td>
</tr>
</tbody>
</table>

Notes: The causality is tested at *10 and *5 per cent significant levels; “No” indicates the corresponding Granger causality is not significant at 10 per cent level; – indicates the direction of influence

3. Methodologies of panel error correction models

Panel regression methods are widely applied to studies into house prices to capture the heterogeneity and correlations across different regions or cities. This section introduces a systematic approach to a panel error correction model which explores spatial autocorrelation of house prices across different cities. The panel error correction model developed in this section takes into account the impacts of long-run equilibrium relationships, short-run dynamics and urban heterogeneity on house price movements. The long-run equilibrium relationships in each individual capital city are represented by the relationships between the house prices in a dominant region and the corresponding city. The SUR method, which considers contemporary correlations between regions, is employed to calculate the estimates of the model (Hsiao, 2003).

Denote $p_i$ and $p_0$ as the logarithm values of house prices in region $i$ and the dominant region at time point $t$, respectively, and $\Delta \bar{p}_i$ as the change of house prices. An individual equation for a non-dominant region in the panel model is expressed as follows:

$$\Delta \bar{p}_i = \alpha_i + \gamma_i (p_{i,t-1} - p_{0,t-1}) + \sum_{j=0}^{N} \beta_{ij} \Delta \bar{p}_{j,t-1} + e_{it}$$

(4)

$a_i, i = 1, 2, \ldots , N$ stand for the regional specific effects, $\gamma_i$ indicate adjustment speeds of the long-run relationships between house prices in a specific region and in the dominant region; $\beta_{ij}$ reflect the influential elasticity of the house price movements in other regions as well as the specific region itself. $e_{it}$ are the error terms in the individual equations. The equation for the dominant region is expressed as follows:

$$\Delta \bar{p}_0 = \alpha_0 + \gamma_0 \bar{p}_{0,t-1} + \sum_{j=0}^{N} \beta_{0j} \Delta \bar{p}_{j,t-1} + e_{0t}$$

(5)
Seen from equation (5), heterogeneity between house prices are captured differently to the estimated parameters across regions. Denotes \( x = p - p_0 \), the panel regression model is expressed as:

\[
\Delta P = A + DT + \Delta Q B + E
\]

(6)

where \( \Delta P \) and \( \Delta Q \) are \( NT \times 1 \) vectors. Specifically, \( \Delta P = (\Delta P_0, \Delta P_1, \ldots, \Delta P_N)' \) and \( \Delta P_i = (\Delta p_{i,1}, \Delta p_{i,2}, \ldots, \Delta p_{i,T})' \), where \( D = (D_0, D_1, \ldots, D_N)' \), where \( D_i = (d_{i,0}, d_{i,1}, \ldots, d_{i,-1})' \) and \( \Delta Q = (\Delta Q_0, \Delta Q_1, \ldots, \Delta Q_{T-1})' \), where \( \Delta Q_i = (\Delta q_{i,1}, \Delta q_{i,2}, \ldots, \Delta q_{i,N})' \), respectively. \( A \) and \( E \) are the estimated regional specific effects and error terms, respectively, which are \( NT \times 1 \) vectors and expressed as \( A = (a_0, \ldots, a_0, a_1, \ldots, a_N) \) and \( E = (e_{0,1}, \ldots, e_{0,T}, \ldots, e_{N,1}, \ldots, e_{N,T}) \). \( \Gamma \) and \( B \) are estimated \( NT \times 1 \) vectors. They are expressed as \( \Gamma = (\Gamma_0, \Gamma_2, \ldots, \Gamma_N) \) and \( B = (B_0; B_2; \ldots; B_N) \). The SUR method is used to estimate the coefficients. This procedure is able to address the problems associated with the presence of cross-sectional dependency among the regional house prices, assuming the error terms of different equations, \( 1_i \), should be correlated with each other contemporarily. That means the variance-covariance of the error terms should be calculated by:

\[
E(\varepsilon_i \varepsilon_{k}) = \begin{cases} 
\sigma^2, & t = s \\
0, & \text{otherwise} 
\end{cases}
\]

Impulse response functions are widely used to study the effects of policy based on a VAR in the traditional econometrics field. The impulse response based on VAR indicates the dynamic effects on each variable when a shock is injected into the system, termed “innovation”, accordingly, a system can be characterised by plotting the impulse response functions (Greene, 2002). This research applies the impulse response function to the panel error correction model. By doing so, it can simulate the house price spatial correlation across different cities, after a shock has occurred to the house prices in the dominant region. According to equation (6), \( \Delta P_i \) can be expressed in terms of current and lagged values of the error term \( E \), in which case the solution of \( \Delta P_i \) is:

\[
\Delta P_i = (I - \Pi L)E_t
\]

(7)

where \( I \) is an identity matrix, \( L \) is the lag operator, and \( \Pi \) is depended on the estimated coefficient matrices \( \Gamma \) and \( B \). Denotes \( \Psi_j \) is an \((N+1) \times 1\) vector with a unit in the \( i \)th element and zero in the other. The house price dynamics over the observation period can be derived from the generalised impulse response function (Pesaran and Shin, 1998) as follows:

\[
\Delta P_{is} = \frac{\Psi_s \sum_{t=0}^{\infty} \Pi_t}{\sigma^2}, \quad \Psi_s = \Gamma \Psi_s-1, \quad \text{with} \quad \Psi_0 = I_{N+1}
\]

(8)

4. Investigating house prices in Australian capital cities via the panel error correction model

4.1 Temporal and spatial interconnections of house prices in Australian capital cities

The panel error correction model expressed as equations (4) and (5) were applied to uncover the interconnections between HPI in the Australian capital cities. The estimated correlation coefficients are reported in Table IV. As Melbourne was selected as the dominant housing market, its long-run relationship term was represented by its previous prices. The constant estimates of the panel error correction model are positive in all the capital cities, with the exception of Melbourne, indicating the house price growth rate is as high as 0.0259 in Darwin, but as low as 20.0838 in Melbourne. The negative urban house price growth rate in Melbourne suggests its house price level is under the average house price level in Australian capital cities. The estimate of long-run relationships in Melbourne is 0.0196, suggesting the house price levels in Melbourne are not stationary. The estimates of the long-run relationships in other capital cities are all negative. This indicates that the house price levels in the other cities move proportionally together with the house price.
levels in Melbourne, in the long-run perspective. In other words, an equilibrium relationship exists between the house price levels in Melbourne and in each of the other cities.

Table IV. Estimations of the panel error correction model

The smaller the values of the estimates are, the sooner the house price levels in the corresponding cities will reach the equilibrium. As observed from Table IV, Adelaide has the smallest value of the long-run estimate, suggesting the house price levels in Adelaide will move first together with the levels in Melbourne, while Sydney with the largest value of the estimate tends to be the last city reaching the long-run equilibrium. The estimates, reported in the row of previous house price movements, illustrate the short-run affects of house price dynamics on the house price movements. Both the positive and negative estimates are observed. In Melbourne, the house price movements are negatively affected by the previous house price dynamics in Adelaide, Brisbane, Darwin, Hobart and Melbourne. In addition, house price movements in Adelaide and Hobart are also negatively correlated with their individual previous dynamics. The house price movements in Brisbane, Canberra, Darwin and Perth are more influenced by their own temporal lags. For example, a one unit increase in the previous house price levels in Perth can turn out to be over a 0.70 increase in its current house price growth. The house price movements in the remaining four capital cities depend more on the previous house price dynamics in the neighbouring capital cities. For instance, a change in Sydney
4.2 Comparison of the developed panel error correction model with the VAR model

For the purpose of evaluating the forecasting accuracy of the panel error correction model, a comparison was conducted with results generated from a VAR model. Two evaluation statistics, mean absolute percentage error (MAPE) and root mean square error (RMSE), were applied to the estimates of the panel error correction model and the VAR model, respectively. As mentioned above, the VAR model failed to take into account the heterogeneity of the capital cities, and the long-run equilibrium relationships of house prices in Australian capital cities were assumed to be the same. Since Melbourne proved to be the dominant housing market among the Australian capital cities, the long-run equilibrium relationship was estimated by

\[ p_{med} = c + \sum_{j=1}^{7} P_j + u_t. \]

Subsequently, the VAR model was established as follows:

\[ \Delta p_d = \alpha_i + \gamma_i \text{ecm} + \sum_{j=1}^{N} \beta_{ij} \Delta p_{d, t-1} + \epsilon_{it}. \]  

(5)

where \( \text{ecm} = p_{med} - c - \sum_{j=1}^{7} P_j \) is an error correction term in the VAR model. The estimates of the VAR model are reported in Table V.

The MAPE and RMSE were calculated for the panel error correction model and VAR model, respectively. The results are reported in Table VI. The MAPE for the error correction model is 2.2975, indicating that the average absolute percentage error is less than 5 per cent over the observed period. A relatively small RMSE, at 0.0030, also reflects that the error correction model fits the data well. It is also confirmed that the MAPE and RMSE for the error correction model are better than the evaluation values for the VAR model, suggesting that the panel error correction model performs better than the VAR model in fitting the data. Considering the advantages of the panel error correction model against the VAR model as discussed above, this research further investigates the house price movements of the Australian capital cities by using the panel error correction model.

Table V. Estimations of the VAR model
5. Spatial correlation patterns of the house prices in Australian capital cities

To investigate the spatial correlation patterns of house prices in Melbourne with other capital cities, this research employs the impulse response function based on the estimated panel error correction model. By plotting the results of the responses in each capital city, the spatial correlation patterns which commenced in Melbourne were generated. Figure 1 shows the responses of the house price movements in Australian capital cities, when a one unit shock has occurred in Melbourne.

As observed in Figure 1, the house price movements in Melbourne were negatively correlated with their previous behaviour. A one unit initial increase in the house prices in Melbourne potentially caused the house price level to decrease by about 0.07 in the first subsequent period and reaching the lowest point at about 20.33 in the third period, with an increase of about 0.06 in the second period. In the remainders of the observation periods, Melbourne house price movements fluctuated within the range of 20.1-0 tended to stabilise at about 20.09. The influencing depth of a shock on Melbourne house prices appears to be a three-quarter delay in reaching its peak, suggesting that the Melbourne housing market may not have been directly influenced directly by its previous housing dynamics in a short-run perspective. The changes in

<table>
<thead>
<tr>
<th>House price movements (Δp)</th>
<th>Constant (α)</th>
<th>Long-run relationship</th>
<th>Previous house price movements (Δp_t-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melbourne</td>
<td>0.0017</td>
<td>0.072</td>
<td>-0.155</td>
</tr>
<tr>
<td>Sydney</td>
<td>0.0092</td>
<td>0.024</td>
<td>-0.116</td>
</tr>
<tr>
<td>Perth</td>
<td>0.0051</td>
<td>0.079</td>
<td>-0.022</td>
</tr>
<tr>
<td>Adelaide</td>
<td>0.0089</td>
<td>0.030</td>
<td>-0.030</td>
</tr>
<tr>
<td>Hobart</td>
<td>0.0041</td>
<td>0.071</td>
<td>-0.031</td>
</tr>
<tr>
<td>Darwin</td>
<td>0.0033</td>
<td>0.078</td>
<td>-0.033</td>
</tr>
<tr>
<td>Canberra</td>
<td>0.0086</td>
<td>0.037</td>
<td>-0.038</td>
</tr>
<tr>
<td>Hobart</td>
<td>0.0041</td>
<td>0.071</td>
<td>-0.031</td>
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<td>0.0033</td>
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</tr>
<tr>
<td>Canberra</td>
<td>0.0086</td>
<td>0.037</td>
<td>-0.038</td>
</tr>
</tbody>
</table>

Note: The long-run relationship in the VAR model is expressed as: \(1 + \alpha_1 + \alpha_2 + \cdots + \alpha_q + p_{t-1} = \beta_1 + \beta_2 + \cdots + \beta_q + \epsilon_t\).
Melbourne house price levels do not reduce to zero, indicating the initial shock should cause a long-run impact on its house price levels. The responses of house price movements in the other cities were significant in the early periods and approached zero, with the exception of Darwin. Specifically, the degrees of influence in the house price movements in Adelaide, Canberra, Perth and Sydney were highest in the first period, while the degrees in Brisbane, Darwin and Hobart reached their own peak with a two-quarter or three-quarter delay. This suggests the house price shock in Melbourne could spread immediately to the housing markets in Adelaide, Canberra, Perth and Sydney, where the house price levels adjusted against effects of the initial house price shock in Melbourne. On the other hand, the house price movements in Brisbane, Darwin and Hobart responded to the initial shock in Melbourne with a temporal delay, indicating the Melbourne housing market may not directly influence the housing markets in these three capital cities. Their responses could be caused by the house price dynamics that were directly affected by the housing market in Melbourne. The responses of house price movements in Darwin continued over 0.02 five years after the initial shock in Melbourne. This does not indicate the house price shock in Melbourne should have a long-run impact on the housing market in Darwin, considering the unique housing policy and location in Darwin. Rather than being influenced by the housing market in Melbourne or other capital cities, the long-run house price increases observed in Darwin could be caused by local housing market and urban characteristics of the region.

To summarise the findings generated by the impulse response function, the spatial correlation patterns of house prices in the Australian capital cities were integrated and are shown in Figure 2. The housing markets in the eight capital cities were catalogued into four levels. Melbourne, as the dominant housing market, is allocated to the top, followed by Adelaide, Canberra, Perth and Sydney in the second level. Brisbane and Hobart are located at the third level, while Darwin is on the bottom.

Figure 1. Responses of HPI movements to one unit shock in Melbourne
The spatial correlation patterns of house prices in Australian capital cities demonstrate the house price dynamics initially occurred in Melbourne. The effects generated from the initial shock subsequently spread to the housing markets in the cities, located at the second level. Meanwhile, interconnections exist among the housing markets in Adelaide, Canberra, Perth and Sydney, which enables the effects to spread across the housing markets in the capital cities at the same level. The effects generated from the housing markets in the second level can also return to the housing markets in Melbourne, via Adelaide. Housing market in Canberra is viewed as a gateway between the housing markets located at second and third levels. A house price movement in Canberra can impact on the house price levels in Hobart and Brisbane directly. Housing market in Darwin, which is located at the bottom, can be directly influenced by the house price dynamics in Hobart and Brisbane; however, it cannot influence the housing markets in the other capital cities.

The results of this research confirmed the proposal made by Meen (1999) that spatial correlation patterns in house prices are caused by geographical and economic characteristics. The spread of an initial shock in the house prices in a dominate city is carried by the migrations of labours and transmission of equities. The central location and strong economy of Melbourne determines the dominant role it holds in the housing markets across the Australian capital cities. The cities located in the second level are either a relatively short distance from or similar economic scales to Melbourne. An increase in Melbourne’s house price may drive labourers move to the nearby cities – Adelaide and Canberra. Meanwhile, investors can shift equity from Melbourne to housing markets with similar scales, such as Perth and Sydney. The transmission of labour and equity can lift house prices in the corresponding cities, which then lowers house price in Melbourne. The responses of house prices to the initial shock in Melbourne appear to be one-quarter lagged in the third-level cities. An initial shock in the housing market in Melbourne can hardly influence the housing market in Darwin, which is the farthest distance away and has the most different economic scale from it.

Figure 2. Spatial correlation patterns of the house price levels

The spatial correlation patterns of house prices in Australian capital cities appear to be spread hierarchically, along with the geographical location and the economic sales of the cities. The findings provide the spatial correlation among the unsystematic part of property returns across the capital cities, which can help financial organisations to make appropriate decisions on portfolio construction. For example, when banks use geographically diversified portfolios of mortgages to maintain capital adequacy, the risk of a portfolio, which contains mortgages of properties in the cities at the first two levels, is better diversified than a portfolio, which is composed by mortgages across all capital cities.

6. Conclusions
This research employed a panel error correction model to explore the spatial correlation patterns of house prices in Australian capital cities. A dominant housing market was identified using the two stage Engle-Granger test and VAR Granger causality tests. Impulse response functions based on the developed panel error correction model were further implemented to simulate the responses of house price movements in the capital cities to a one unit shock in the house price level in the dominant housing market. Three major conclusions can be reached.

First, the results of Engle-Granger and Granger causality tests confirmed Melbourne was identified as the dominant housing market, where the house price levels were cointegrated with the house price levels in other capital cities. The house price movements in Melbourne could significantly influence in the housing markets in other capital cities but could not be influenced.

Second, the house price levels in Melbourne failed to reach a constant level in the long-run, while long-run equilibrium relationships were confirmed between the house price levels in Melbourne and other capital
cities. The housing market in Adelaide approached its equilibrium first, while the approach speed in Sydney was the slowest. In addition, the previous house price change in Melbourne caused significant short-run impacts on the house price dynamics in Adelaide, Canberra, Perth and Sydney immediately, while delayed influences appeared in Brisbane, Darwin and Hobart.

Third, the spatial correlation patterns of house price levels in the Australian capital cities were confirmed by integrating the results of the impulse response function. The house price dynamic commenced in Melbourne initially, with the effects spreading immediately to the housing markets in Adelaide, Canberra, Perth and Sydney. The house price movements in the cities located at the first and second levels influenced the house price movements in Brisbane and Hobart via the housing market in Canberra. The housing market in Darwin was influenced by the housing markets in Brisbane and Hobart, but could not influence in other capital cities.

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