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Robert J. **HILL**[1]
Miriam **STEURER**[1]
Sofie R. **WALTL**[2]

[1] University of Graz, Austria
[2] LISER, Luxembourg

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Robert J. Hill[1], Miriam Steurer[2] and Sofie R. Waltl[3]

[1] Department of Economics, University of Graz, Universitätsstrasse 15/F4, 8010 Graz, Austria, robert.hill@uni-graz.at

[2] Department of Public Economics, University of Graz, Universitätsstrasse 15/E4, 8010 Graz, Austria, miriam.steurer@uni-graz.at

[3] Luxembourg Institute of Socio-Economic Research, Maison des Sciences Humaines, 11 Porte des Sciences, 4366 Esch-sur-Alzette / Belval, Luxembourg, sofie.waltl@liser.lu

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Abstract:
The treatment of owner-occupied housing (OOH) is probably the most important unresolved issue in inflation measurement. The European Union has been grappling with this problem for over a decade. We argue for measuring OOH costs using a particular version of the user cost method. We then compare the impact of eight different treatments of OOH on the consumer price index (CPI), using quantile hedonic regression. The impact on the CPI is large, and the treatment of OOH emerges as an essential prerequisite to discussions over how an inflation targeting central bank should respond to housing booms and busts. (JEL. C31; C43; E01; E31; E52; R31)

Keywords: Measurement of inflation; Owner occupied housing; User cost; Quantile regression; Hedonic imputation; Housing booms and busts; Inflation targeting

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1 Introduction

> The big question for inflation measurement -– as big as the decision about how to treat government expenditures in calculating GDP -– is whether to include owner-occupied housing in aggregate consumer price statistics. And if the answer is that we should, which I think it is, then how should we do it? (Cecchetti, 2007, p. 1)

The consumer price index (CPI) is the main measure of inflation used by central banks for setting monetary policy. The CPI is also used by the government and private sector to index wages, pensions, and contracts. Our focus here is on the measurement of inflation as it pertains to monetary policy. In this context, the objective of the CPI is to measure the purchasing power of money. The relevant basket consists of all goods and services, including housing, consumed by households.

There is broad agreement on how rents should enter the CPI. The problematic part of housing is owner occupied housing (OOH). There is some agreement that, one way or another, OOH should be included in the CPI, as a change in house prices affects consumer prices, and hence the purchasing power of money (see for example Goodhart 2001, Diewert 2003, Cecchetti 2007, and European Central Bank 2016).[1] The problem is how to include it.

OOH, when included, is typically the biggest component of the CPI. However, many countries exclude OOH from their CPIs on the grounds that it is too difficult to measure. In particular, the harmonized index of consumer prices (HICP) in the European Union (EU) currently excludes OOH.[2] The HICP is the flagship CPI in the EU that is used by the European Central Bank (ECB) for price stability purposes as well as for assessing whether countries are ready to join the euro area. As the following quote illustrates, there is a general desire to include OOH in the HICP once the measurement problems have been sufficiently resolved.

[1] The situation is less clear with regard to a CPI used for the indexation of wages and pensions, since any increase in the cost of OOH services is offset by the extra imputed rent received. Also, it may be desirable to construct separate indexes for owner occupiers and renters. In short, OOH in a CPI used for indexation of wages and pensions deserves its own separate treatment.

[2] The HICP is jointly compiled by Eurostat (the statistical institute of the European Union) and national statistical institutes following a harmonized statistical methodology.

> Establishing price indexes for dwellings, and in particular for owner-occupied housing (OOH), is an important step towards further improving the relevance and comparability of the HICP. [...] By 31 December 2018, the Commission should prepare a report addressing the suitability of the OOH price index for integration into the HICP coverage. (Source: Regulation 2016/792 of the European Parliament and of the Council of 11 May 2016, Official Journal of the European Union, 24.05.2016, L 135/12, paragraph 10)

The three main methods for including OOH in the CPI are acquisitions, rental equivalence and user cost (see for example Blinder 1980, Diewert 2003, 2009, and Eiglsperger 2006). Of these, rental equivalence is the most widely used. Even though a number of European countries use rental equivalence in their national CPIs, Eurostat recommends the acquisitions method (see Eurostat 2012) for use in the HICP.[3] By contrast, we show that the user cost method when implemented in our preferred way has the advantage that it has both better theoretical properties than the rental equivalence and acquisitions methods, and is easier to use in practice.[4]

Implementation of the user cost approach however encounters two main problems, which are probably the reason why it has not been used more widely thus far. The first problem is the treatment of capital gains. In contrast to much of the existing academic literature, we argue that capital gains should be excluded from OOH expenditure in the CPI. Indeed this is what all three countries currently using the user cost method – Canada, Sweden and Iceland – are already doing. We present three reasons for excluding capital gains. Most importantly, we show that including capital gains imparts a downward bias to the CPI.

[3] Most EU countries are computing experimental HICPs that include OOH using the acquisitions method.

[4] Another method – the payments approach – has also been proposed in the literature, but in our opinion it lacks sufficient theoretical foundations to warrant consideration here. Austria and Ireland are the only countries, that we are aware of, that still use it. The weaknesses of the payments approach are discussed in Diewert (2003, 2009). More recently, Diewert, Nakamura and Nakamura (2009) have proposed another method – the opportunity cost method – that sets the cost of OOH equal to the maximum of rental equivalence and user cost. This maximum should in principle be calculated at the level of each individual dwelling. This method has not yet been tested on real data.

The second problem, arising from the interest rate term in the OOH expenditure formula, is that the immediate impact of a contractionary monetary policy during a housing boom may be to increase the measured rate of inflation – the exact opposite of what the central bank intended. This concern can be partially dealt with by using a long term (e.g., 10-30 year) interest rate in the user cost formula, since long term rates tend to be less sensitive to changes in the target rate (see Jordá 2005). In section 2.3, we argue that, if this is not sufficient, an alternative could be to use the natural rate of interest (i.e. the interest rate that equates investment and saving at full employment – see Summers 2016).

It is important also to know how the alternative methods for including OOH in the CPI perform empirically, and how much difference it makes which method is used. For this purpose we use a detailed micro-level dataset consisting of over 1 million price and rent observations from Sydney (Australia) over the period 2004-2014.

We use hedonic models estimated using quantile regression methods to impute prices and rents for every dwelling in every year. The use of quantile regression methods ensures that prices and rents in all parts of the price and rent distributions are imputed as accurately as possible. A number of methodological innovations are introduced here, and hence our quantile based estimation by itself constitutes a significant contribution (see Appendix B).

With these imputed prices and rents we then empirically compare eight versions of the CPI for Sydney that differ in their treatment of OOH. These are the rental equivalence method, four variants on the user cost method, Eurostat's version of the acquisitions method, a CPI that excludes OOH, and the official CPI for Sydney, computed by the Australian Bureau of Statistics (ABS) using its own version of the acquisitions method.

We show that the treatment of OOH significantly affects the average rate of inflation in Sydney. For example, over our sample period, the average annual inflation rate based on our preferred user cost method is 0.47 percentage points higher than the official inflation rate.

We then consider the implications of our results for monetary policy. Our empirical analysis demonstrates that the sensitivity of the CPI to the treatment of OOH depends on how rapid and sustained the appreciation of real house prices is. Knoll, Schularick and Steger (2017) have collected data for 14 OECD countries that show that real house prices have been rising quite rapidly in most of these countries since 1950, thus implying that the treatment of OOH could have a very significant impact on the CPI in these countries.

The implications of this are striking for countries that currently exclude OOH from their CPIs. A particular focus of attention in this regard is the ECB, given that the HICP currently excludes OOH. During a housing boom, the inclusion of OOH tends to push up the CPI, especially when our preferred version of the user cost method is used. In other words, an inflation targeting central bank would automatically engage in some "leaning against the wind" (i.e., raising interest rates in response to a housing boom). There is a vigorous ongoing debate over whether central banks should actively "lean" on housing booms (see Cecchetti 2006, Mishkin 2011, Adam and Woodford 2013, and Svensson 2016). An important insight of our paper is that a prerequisite to this debate is to first assess how OOH is being treated in the central bank's target CPI, since the default position may already imply a certain degree of "leaning".

The remainder of the paper is structured as follows. Section 2 discusses the main features of the acquisitions, rental equivalence and user cost methods for including OOH in the CPI, and explains why we prefer user cost. Section 3 makes the case for excluding capital gains under a user cost approach, and in particular shows how including capital gains causes a downward bias in the CPI. A more detailed discussion on this last point is provided in Appendix A. Section 4 compares the methods discussed in sections 2-3 empirically using micro-level data from Sydney, Australia. Section 5 considers the implications of our results for monetary policy. Our main findings are summarized in section 6.

2 Ways of Including OOH in the CPI

2.1 The acquisitions approach

The acquisitions approach is used by Australia, New Zealand, Finland, and on an experimental basis by the member states of the European Union, although OOH is not currently included in the headline HICP in Europe.

Expenditure on OOH under the acquisitions approach consists of three components:

$$\begin{aligned} Y_t = & \text{New dwelling purchases by owner-occupiers (excluding land)} \\ & + \text{Maintenance and repair of dwellings} \\ & + \text{Property rates and charges.} \end{aligned}$$

The first of these components, which also includes major renovations and existing dwellings that are new to the residential sector, is by far the largest. It can be taken straight from new residential construction in the national accounts. The other two components may require additional data collection.

The average expenditure per household, y_t^A, is obtained by dividing Y_t through by the total number of households H_t (i.e., both owner-occupiers and renters): $y_t^A = Y_t/H_t$.

Australia and New Zealand differ from Europe in the way that the price index for new dwelling purchases by owner-occupiers is constructed. Australia and New Zealand use cost indexes for residential construction building materials. By contrast, Eurostat recommends using price indexes for new residential housing based on actual transaction prices (see Eurostat 2012). As transaction prices contain the cost of land as well as structure, the land component is hence included in the price index.

The main rationale for the acquisitions approach is that it treats OOH in the CPI in the same way as consumer durables such as cars and refrigerators. However, a house is different from a car or refrigerator in that it consists of land and a structure. While the structure is produced, the land is not. The acquisitions approach, at least with regard to the OOH expenditure share, focuses exclusively on the structure, and hence ignores the role played by land. But land prices are generally the driving force in house price increases. Based on a sample of 14 OECD countries, Knoll, Schularick and Steger (2017) show that almost all of the rise in real house prices since 1870 can be attributed to changing land prices. Davis and Heathcote (2007) obtain similar results across regional metropolitan statistical areas in the United States. Omitting land therefore deprives OOH of most of its content.[5]

[5] Admittedly, while it excludes land from the OOH expenditure share, as was noted above, the Eurostat

A further weakness of the acquisitions approach is that new residential construction is a very volatile component of GDP, that rises strongly during housing booms only then to collapse when house prices start falling (see Leamer 2007). Hence the expenditure weights on OOH under the acquisitions approach can fluctuate very significantly over the housing cycle. If the weights are updated regularly this may have a destabilizing effect on the CPI. If the weights are not updated regularly, then the treatment of OOH may be highly sensitive to the choice of reference year.

In the European context, this issue could be particularly problematic given that the housing cycles of many euro area countries seem to be out of sync with each other.[6] In any given period, euro area countries with rising house prices will tend to have large expenditure weights for housing, while countries with stagnant housing markets will tend to have small expenditure weights, thus potentially undermining the comparability of the HICP across countries.

Even when housing cycles are aligned, the international comparability of new residential construction, as recorded in the national accounts, could be quite poor. For example, the proportion of new houses that are self-builds can vary enormously across countries, as can the ability of national statistical institutes (NSIs) to record self-building activity. Related to this is the problem of distinguishing between renovations and repairs. Under the acquisitions approach, renovations and repairs should be included in different headings. Inconsistencies across countries could arise if these definitions are not carefully harmonized.

Finally, as was noted above, the Eurostat version of the acquisitions method requires, where possible, a price index for newly built housing. Constructing such an index may be extremely problematic for some countries when the number of new dwelling sales recorded each period is low. This can happen when the country has a small population, a high proportion of self-builds, or when it is experiencing an economic downturn.

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version of acquisitions does include land in the price index.

[6]For example, while German and Austrian house prices were falling/stable from 1990 to 2007, Spanish, and Irish prices were rising strongly. This pattern reversed once the euro area crisis started.

2.2 The rental equivalence approach

Rental equivalence is the most widely used method for including OOH in the CPI. It is used for example by the USA, Japan, Denmark, Norway, Switzerland, the Czech Republic, Mexico, and South Africa in the CPIs used for monetary policy (see OECD 2015). For wage indexation purposes, Germany, the Netherlands, and the UK use a CPI that includes a rental equivalence version of OOH (see Office of National Statistics 2016a).[7]

Both the rental equivalence and user cost approaches attempt to measure expenditure on OOH services. Focusing on the stream of services provided by OOH ensures consistency with the treatment of rental dwellings, where the focus is also on the stream of services provided.

Given that OOH services are derived from both the structure and land it follows that there is no need to try and separate land from structure in the house price index. Rental equivalence as the name suggests imputes a rental expenditure for owner-occupied dwellings. This is usually done with surveys of owner-occupiers who are asked the hypothetical question: How much do you think your dwelling would cost to rent?

Average household expenditure on OOH under rental equivalence (y_t^R) is the average imputed rent on OOH dwellings ($\bar{R}_t$):

$$y_t^R = \bar{R}_t \times \frac{H_t^{OOH}}{H_t}, \tag{1}$$

where H_t^{OOH} is the number of OOH households while H_t is the total number of households.

To implement the rental equivalence approach therefore the imputed average rent of OOH dwellings, $\bar{R}_t$, is required, along with the share of owner-occupiers, H_t^{OOH}/H_t, and a rental price index.

While it is an improvement on the acquisitions approach, rental equivalence has some weaknesses. In particular, it does not answer the right question. The services a household obtains from renting a dwelling are not the same as the services obtained by owner-occupying. An

[7] The UK is an interesting case. It is in the process of switching from the HICP – known as the CPI in the UK – to CPIH (an index that includes OOH using rental equivalence) for indexation purposes. Thus far the Bank of England has not stated any intention to likewise switch from the CPI to CPIH for monetary policy purposes.

owner-occupier can live in the dwelling indefinitely. A tenant, by contrast, knows that, when the lease expires, the rent could be increased, or the contract terminated. Hence maintenance, improvements, and local amenities are likely to be valued more by owner occupiers. Also, moving from one rental dwelling to another at short-notice incurs substantial transaction costs (in time, money, and stress).

It could be argued that rental equivalence provides a good approximation to the cost of owner occupying. While this claim may be reasonable in some countries (or parts thereof), in others the rental market is not a good indicator of OOH costs, since a significant part of the rental market is subject to rent control, or the rental market is too small, concentrated in the urban areas, and/or dominated by certain groups (e.g. expatriates or students). This is an important issue in the European Union. The HICP requires that all member states use the same method to measure the costs of OOH. However, the share of the rental market of most Eastern European countries lies below 10 percent, and for some western EU countries such as Spain and Italy it is less than 20 percent.[8]

In cases where the rental market is large and deregulated enough, estimates of rental prices for OOH can be imputed using hedonic methods.[9] Imputing rents from a hedonic model, however, can be problematic since owner-occupied dwellings tend to be of systematically higher quality than rental dwellings, even when one controls for observed characteristics, such as location, number of bedrooms, and land area (see Halket, Nesheim, and Oswald 2015, and Hill and Syed 2016).

An alternative to estimating imputed rents using matching statistical methods is to survey owner-occupiers. Anecdotal evidence suggests that survey estimates may be too high either because owners are overly optimistic or because they value the particular features of their property more than the average renter (see Heston 2009, and Heston and Nakamura 2009).[10]

[8] See http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ilc_lvho02&lang=en.

[9] In spite of the small rental market in Spain, Arévalo and Ruiz-Castillo (2006) find that imputed rents obtained from a simple hedonic model match quite well with owner's own estimates of the potential rent they could earn from their dwellings.

[10] This latter point is another indication that owner-occupiers and renters obtain different services from the same dwelling, and hence that rental equivalence is not measuring the right thing.

Above that, owner-occupiers often do not participate in the rental market and may hence be less informed about current market rents. In addition to these conceptual problems, imputing rents by matching or from surveys is costly and time intensive.

Turning now to the OOH price index, to capture the current state of the market the index should focus on new, rather than existing, rental contracts. A quality-adjusted index based on new rental contracts can be computed using hedonic methods. By contrast, the normal practice is to follow the same dwellings over time (see for example Office of National Statistics 2016b).

There is ample evidence that rent indexes and price indexes can follow very different paths over the short to medium term (see for example Hill and Syed 2016). Rental equivalence has even been implicated in contributing to the global financial crisis (GFC), in that rental prices hardly rose in the US during the housing boom that ended in 2006. Hence, the development of the house price bubble did not put inflationary pressure on the US CPI, and there was no contractionary impact on monetary policy.

Such a situation is not uncommon during booms, which are often driven by the expectation of future capital gains rather than rising rents. Indeed, in this regard it is informative to consider Stiglitz's (1990) definition of a bubble.

> [I]f the reason the price is high today in *only* because investors believe the selling price will be high tomorrow – when "fundamental" factors do not seem to justify such a price – the a bubble exists. (Stiglitz, 1990, p. 13)

The rental equivalence approach is therefore not only likely to fail but actually expected to fail to register the presence of a bubble. This is problematic from a monetary policy standpoint.

2.3 The user cost approach

Versions of the user cost method are used in the official CPIs of Canada (see Baldwin, Nakamura, and Prud'homme 2009, and Sabourin and Duguay 2015), Sweden (see Johansson 2006), and Iceland (see Gudnason and Jónsdóttir 2009 and Diewert 2009).

The basic idea of the user cost approach dates back at least to Keynes (1936). The approach was developed by Jorgenson (1967) and Hall and Jorgenson (1967) to provide an imputed rent for purchased capital used by firms in production. The concept can equally well be applied to housing to measure the cost of OOH services directly (see Blinder 1980 and Poterba 1984). For each dollar invested in OOH the user cost is usually assumed to consist of the following components (or something similar):

$$u_t = r_t + \delta_t + \omega_t + \gamma_t - \pi_t - g_t, \tag{2}$$

where

u is per dollar user cost,

r is the interest rate,

δ is depreciation,

ω is running and average transaction costs (including taxes),

γ is the risk premium,

π is the expected rate of inflation and

g is the expected real capital gain on housing.

The formula includes an additional term if owner-occupiers can tax deduct mortgage interest payments (again see Blinder 1980). However, since owner-occupiers cannot tax deduct mortgage interest payments in Australia, we omit this term here.

The formula in (2) is a simplification of a more general user cost formula provided by Diewert (2003):

$$u_t = (1 + r_t) - (1 - \delta_t - \omega_t - \gamma_t + \pi_t)(1 + g_t) = r_t + \delta_t + \omega_t + \gamma_t - \pi_t - g_t + (\delta_t + \omega_t + \gamma_t - \pi_t)g_t.$$

A similar specification is derived in Christensen and Jorgenson (1969). The Diewert formula reduces to (2) when it is assumed that

$$(\delta_t + \omega_t + \gamma_t - \pi_t)g_t \approx 0.$$

In our empirical comparisons, this is a reasonable assumption. Omitting this term has virtually no impact on the results. Henceforth, therefore, we measure user cost using the formula in (2).

Average household expenditure on OOH (y_t^U) under the user cost approach is calculated as follows:

$$y_t^U = \bar{P}_t u_t \times \frac{H_t^{OOH}}{H_t}, \tag{3}$$

where $\bar{P}_t$ is the average estimated price of an OOH dwelling in period t, and H_t^{OOH}/H_t is again the share of households that are owner occupiers.

To implement the user cost approach it is therefore necessary to compute the per dollar user cost u_t, the average price of OOH dwellings $\bar{P}_t$, a hedonic house price index, and the share of households that are owner-occupiers.

Given the problems with acquisitions and rental equivalence discussed above, why then is the user cost approach not currently used by more countries? This is probably because each of the components of the per dollar user cost u_t in (2) is somewhat problematic.

We can separate u_t into three parts as follows:

$$u_t = (r_t - \pi_t) + k - g_t. \tag{4}$$

where $k = \delta + \omega + \gamma$. There are no time subscripts on k because its components (i.e., depreciation, running and average transaction costs, and the risk premium) are assumed to remain constant over time. While deciding on reasonable estimates of δ and ω is not entirely straightforward, each country should be able to do this. If, with more experience, the initial estimate is deemed incorrect it can be adjusted. Canada for example in 1998 revised downwards its estimate of depreciation from 2 percent to 1.5 percent (see Baldwin, Nakamura, and Prud'homme 2009). Also, any error in δ and ω will have the same impact each period, and hence should not destabilize the index.

A discussion of the treatment of the risk premium γ_t and expected real capital gain g_t is deferred to the next section. For the moment it suffices to say that all countries using the user cost approach set both these terms to zero, and that we support this decision.

The remaining terms in (4) are the nominal interest rate r_t and the expected rate of inflation π_t. The expected rate of inflation can be estimated based on past inflation rates, from inflation indexed bonds (when available) or from surveys. One objection sometimes raised by central banks to the user cost approach is that with the inclusion of the interest rate r_t, the immediate impact of a contractionary monetary policy will be to raise the level of inflation – the exact opposite of the policy objective. It should be noted first that this is only true when house prices are rising faster than the general CPI (which admittedly is often the case in such situations). This issue can be partially dealt with by using a long-term interest rate, which should be less sensitive to changes in the central bank's target rate, in the user cost formula. Using a long-term interest rate can also be justified by the high level of transaction costs incurred by participants in the housing market. In section 4 we use the 10-year government bond rate in the user cost formula.

If a long term interest rate is not sufficient to resolve this problem an alternative is to use the natural real rate of interest defined by Summers (2016) as follows:

> Following the Swedish economist Knut Wicksell, it is common to refer to the real interest rate that balances saving and investment at full employment as the natural, or neutral, real interest rate. (Summers, 2016, p.3)

Alternatively, the natural rate is sometimes defined as the real interest rate consistent with output equaling its natural rate and stable inflation (see for example Laubach and Williams 2003). Either way, r_t in (2) would be replaced by the sum of expected inflation and the natural interest rate. The expected rate of inflation then cancels out of (2). While not directly observable, the natural rate of interest is estimated by central banks for use in Taylor rules (see Laubach and Williams 2003), and is not affected by changes in monetary policy.[11]

[11] In the context of the CPI it would probably be desirable to impose a nonnegativity constraint on the natural rate.

3 Capital Gains in the User Cost Approach

3.1 Some possible treatments of capital gains

In what follows we consider three ways of dealing with real capital gains (g_t) when measuring the cost of OOH in the CPI from a user cost perspective.

(i) Include ex post real capital gains. The user cost of OOH can then be written as follows:

$$P_t u_t = P_t \left[x_t - \left(\frac{HPI_{t+1} - HPI_t}{HPI_t} \right) \right], \tag{5}$$

where P_t denotes the price of the average dwelling in period t, u_t is the per dollar user cost, x_t is all components of per dollar user cost except for real capital gains, and HPI_t and HPI_{t+1} are the level of the house price index in periods t and $t+1$, respectively, in constant dollars. The term $(HPI_{t+1} - HPI_t)/HPI_t$ therefore represents the per dollar real capital gain.

(ii) Exclude real capital gains. The user cost of OOH can then be written as follows:

$$P_t u_t = P_t x_t. \tag{6}$$

(iii) Include expected real capital gains. The user cost of OOH can then be written as follows:

$$P_t u_t = P_t \left[x_t - \left(\frac{E_t HPI_{t+1} - HPI_t}{HPI_t} \right) \right], \tag{7}$$

where $E_t HPI_{t+1}$ is the level of the house price index in period $t+1$ expected at the beginning of period t (again in constant dollars). The question now is how do households compute $E_t HPI_{t+1}$? We assume expectations are computed by extrapolating from previous periods in the following way:

$$\frac{E_t HPI_{t+1} - HPI_t}{HPI_t} = \left(\frac{HPI_t - HPI_{t-m}}{HPI_{t-m}} \right)^{1/m}.$$

It is assumed therefore that households compute the compounded rate of return over the last m periods, and then expect this rate of return in period t. Rearranging, we obtain that

$$E_t HPI_{t+1} = HPI_t \left[\left(\frac{HPI_t - HPI_{t-m}}{HPI_{t-m}} \right)^{1/m} + 1 \right].$$

3.2 The case for excluding capital gains

Capital gains g_t are probably the most contentious component of the per dollar user cost u_t. The user cost equilibrium condition states that in equilibrium a household should be indifferent between owner-occupying and renting. Hence the cost of owner-occupying (the user cost) should equal the cost of renting. This yields the following equation:

$$u_t P_t = R_t,$$

which can be rearranged as follows:

$$\frac{P_t}{R_t} = \frac{1}{u_t}.$$

This approach provides an estimate of the equilibrium price-rent ratio. Departures from equilibrium can therefore be detected by comparing the actual and equilibrium price-rent ratios (see for example Himmelberg, Mayer, and Sinai 2005, and Hill and Syed 2016). In this context it makes sense to include expected capital gains in the per dollar user cost u_t, since households will account for expectations of future house price movements when deciding whether to buy or rent.

However, when the objective is to measure the cost of OOH in the CPI the case for including expected capital gains g_t is less clear. A house is partly a consumption good and partly an asset. The CPI should focus on the consumption aspect of housing. The expected capital gain is a change in wealth, and hence relates to the asset dimension. When included in the user cost of OOH, a capital gain is effectively treated like negative expenditure. This goes against the basic principles of the CPI, which focuses on the actual costs directly incurred by households when purchasing and consuming goods and services.

A similar argument can be made with regard to the risk premium (γ_t). While the risk premium belongs in the user cost equilibrium condition, it is not a cost directly incurred by households, and hence most NSIs would argue that it does not belong in the CPI.

It is perhaps not surprising, therefore, that the three countries – Canada, Sweden, and Iceland – that use the user cost method in their CPIs all exclude capital gains and the risk premium.

There are two other good reasons for excluding capital gains. First, expected capital gains are not observed directly, and a few studies (e.g. Verbrugge 2008, Garner and Verbrugge 2009, and Hill and Syed 2016) have shown that the estimated user cost can be highly sensitive to the choice of time horizon for expectation formation for capital gains.

The second reason is that including capital gains (expected or actual) in the user cost of OOH may introduce a downward bias into the CPI. The essential intuition here is that the inclusion of capital gains acts to push down the OOH expenditure share when house prices are rising, and conversely to push up its share when house prices are falling. This point is made by Goodhart (2001), although he does not discuss how this can lead to bias in the index itself.

> [The user cost method measures] the cost foregone by living in an owner-occupied property as compared with selling it at the beginning of the period and repurchasing it at the end. [...] But this gives the absurd result that as house prices rise, so the opportunity cost falls; indeed the more virulent the inflation of housing asset prices, the more negative would this measure become. Although it has some academic afficionados, this flies in the face of common sense. (Goodhart, 2001, p. F351)

The downward bias in the CPI when capital gains are included in OOH costs can be formalized as follows:

> **Proposition**: Suppose over the interval $t = 1, \dots, T$, real house prices rise (or fall) and then return to their original level. Suppose further that over this same interval prices and expenditure of all other components in the CPI remain constant. When real capital gains (actual or expected) are included in OOH costs, the chained CPI will end up lower in period T than it was in period 1.

This proposition implies a systematic violation of Walsh's (1901) multiperiod identity test (see also Diewert 1993). The test can be stated as follows:

$$P(p^1, p^2, q^1, q^2) \times P(p^2, p^3, q^2, q^3) \times \cdots \times P(p^{T-1}, p^{T-1}, q^T, q^T) = 1,$$

where p^t and q^t are the price and quantity vectors of period t. When capital gains are included, we obtain that: $P(p^1, p^2, q^1, q^2) \times P(p^2, p^3, q^2, q^3) \times \cdots \times P(p^{T-1}, p^{T-1}, q^T, q^T) < 1$.

A proof of this proposition for some special cases, and some numerical examples, is provided in Appendix A. We also consider there some numerical examples. These examples illustrate how the extent of the bias depends on the length of the time horizon over which expectations are formed relative to the length of the cycle in house prices. Holding the length of the price cycle constant, as the expectation formation horizon gets longer the magnitude of the bias decreases. It disappears completely once the expectation formation time horizon is longer than the price cycle.

3.3 The simplicity of the user cost method

The calculation of the elements of u_t in (2) becomes quite straightforward when the user cost formula is simplified in the way we recommend (i.e. γ_t and g_t are excluded, r_t is a long-term interest rate, and long-term averages for δ and ω are used). The most challenging part of computing average household expenditure on OOH (y_t^U) under the user cost approach in (3) is then estimating the average price of an OOH dwelling $\bar{P}_t$ in each period t. Ideally, hedonic methods should be used to compute $\bar{P}_t$. But, if necessary, this average price could be computed as a stratified median.

4 Empirical Strategy

4.1 The data set

Before drawing conclusions it is important to check how the various methods for including OOH in the CPI perform on real data. The data set used here covers the period 2004 to 2014 for Australia's largest city, Sydney. The data set was purchased from Australian Property Monitors (APM).[12] We use 340 362 actual transaction prices (measured in Australian dollars)

[12] APM provides real estate related research service and data for the Australian market. See `http://apm.com.au` in order to obtain access to their data sets.

for houses sold over this period and 215 408 transaction prices for units sold. The data set also includes 311 105 asking rents for houses and 479 211 asking rents for units (the rents are quoted in Australian dollars – AUD – per week).

For each price and rent observation we have information on the following characteristics: exact date of sale (or posting of the asking rent), land area, number of bedrooms, number of bathrooms, exact address, postcode identifier, and exact longitude and latitude. Houses and units with land areas greater than 10 000 square meters, or more than 6 bedrooms or bathrooms were deleted (since a significant number of these outliers contain data entry errors). Above that, observations with unrealistic price or rent information such as a weekly rent of 1 Australian dollar or observations with missing price or rent information or locational characteristics were deleted as well. The longitudes lie within [150.60; 151.35] and the latitudes within [-34.20; -33.40]. Houses or units that are not located in one of Sydney's 16 regions were also excluded.[13] Summary statistics are provided in Appendix C, Table C1.

The data set has some gaps. There are, in particular, many observations lacking the number of bed- or bathrooms. We use a reconstruction algorithm that exploits the fact that some properties appear multiple times in the data sets, as they are both sold and rented, or sold or rented more than once.[14] The reconstruction algorithm checks whether an observation with missing characteristics has been observed at another point in time and refills the missing value if it is available there. The empirical analysis is then performed on all completely observed or successfully refilled observations.

[13]Residex, an Australian provider of property information, divides Sydney into 16 regions: Campbelltown, Canterbury-Bankstown, Cronulla-Sutherland, Eastern Suburbs, Fairfield-Liverpool, Inner Sydney, Inner West, Lower North Shore, Manly-Warringah, Mosman-Cremome, North Western, Parramatta Hills, Penrith-Windsor, St Georges, Upper North Shore and Western Suburbs.

[14]The algorithm applied in this paper is similar to the ones used in Waltl (2017a, 2017b), but extended to cross-refilling between sales and rental observations, and reconstruction of the variable land area.

4.2 Imputing prices and rents for individual dwellings in Sydney

We use hedonic quantile regression models to impute prices and rents for individual dwellings. A quantile approach ensures that imputations for each dwelling are tailored to its part of the price or rent distribution. The imputation procedure consists of five steps which are described in Appendix B.

4.3 Average rents and prices per quarter

Table I reports mean sales and rental prices for the OOH and rental sample obtained from the five-steps procedure described above.[15] Separate means and rents are calculated for houses and units. These are then combined to produce means for the whole market (i.e., with houses and units combined). The whole market mean is a weighted average of the house and unit means. The weights were obtained from estimates of the total stock of houses and units in Sydney. We estimated the stock of sold houses and units by counting the total number of distinct (i.e., excluding repeats) house and unit sales in the data set. Similarly we estimated the stock of rented houses and units by counting the total number of distinct house and unit rentals. The results are as follows:

Total distinct house sales: 281 458; Total distinct unit sales: 167 905;

Total distinct house rentals: 177 023; Total distinct unit rentals: 237 887.

Insert Table I Here

4.4 Construction of hedonic price indexes and rent indexes

Price and rent indexes are shown in Table II and Figure I. These indexes are constructed using the Törnqvist hedonic imputation formula in (10), which is derived from (8) and (9).

[15] Mean prices and rents are consistently higher than median prices and rents as the price distributions are right-skewed.

The price (rent) index for multiple periods is chained.

$$\text{Paasche} - \text{Type Imputation}: \ P^{PI}_{t,t+1} = \prod_{h=1}^{H_{t+1}} \left[\left(\frac{\hat{p}_{t+1,h}(z_{t+1,h})}{\hat{p}_{t,h}(z_{t+1,h})} \right)^{1/H_{t+1}} \right] \tag{8}$$

$$\text{Laspeyres} - \text{Type Imputation}: \ P^{LI}_{t,t+1} = \prod_{h=1}^{H_t} \left[\left(\frac{\hat{p}_{t+1,h}(z_{t,h})}{\hat{p}_{t,h}(z_{t,h})} \right)^{1/H_t} \right] \tag{9}$$

$$\text{Törnqvist Imputation}: \ P^{TI}_{t,t+1} = \sqrt{P^{PI}_{t,t+1} \times P^{LI}_{t,t+1}} \tag{10}$$

In (8) and (9) we focus on houses that are sold. An equivalent formula exists for houses that are rented. The term $z_{t,h}$ denotes the vector of characteristics of a house h that sold in period t, and $\hat{p}_{t+1,h}(z_{t,h})$ refers to the imputed price in period $t+1$ of this house.

Insert Figure I Here

Insert Table II Here

The imputed prices in (8) and (9) are obtained from quantile regression models as described in Appendix B. The price indexes are computed using double imputation, which means that both the numerator and denominator in each price relative are imputed. We have no choice but to impute the denominators in (8) and the numerators in (9) since these prices are not actually observed. However, under double imputation we choose to use an imputation in the numerator of (8) and the denominator of (9) in preference to the actual transaction prices. Double imputation tends to reduce omitted variables bias when the levels of the omitted variables are reasonably stable over time, as is typically the case in the housing market (see for example de Haan 2004, and Hill and Melser 2008).

4.5 Estimating the components of the user cost of OOH

Recapping, the components of user cost as stated in (2) are as follows:

$$u_t = r_t + \delta_t + \omega_t + \gamma_t - \pi_t - g_t.$$

Here we draw on Fox and Tulip (2015) and Hill and Syed (2016) when computing these components for Sydney. We set r_t as the 10-year interest rate on Australian government bonds (Source: Reserve Bank of Australia). The bond rate ranged between a minimum value of 2.89

percent in 2012 and a maximum value of 6.59 percent in 2008. Since structures depreciate while land does not, the appropriate depreciation rate should depend both on the age of the structure and on the share of the structure in the total value of the dwelling. This implies that every dwelling will have its own unique depreciation rate. In the context of the CPI, however, the important thing is to get the average about right. We set depreciation $\delta = 1.1$ percent. This is the depreciation rate estimated by Stapledon (2007) for Sydney and used by Fox and Tulip (2014).

We again follow Fox and Tulip (2014) when setting the running costs plus average transaction costs. They estimate running costs in the Australian context of 1.2 percent (see their Table A1, p. 29).[16] The main components of transaction costs are stamp duty and real estate agent commissions. Average transaction costs are obtained by amortizing the total amount over a ten year period. Again these estimates are obtained from Table A1 in Fox and Tulip (2014). Fox and Tulip estimate average transaction costs to equal 0.7 percent. Combining these components yields a total of 1.9 percent.

Following Fox and Tulip (2014) we exclude the risk premium. The expected rate of inflation π_t is assumed to be 2.5 percent. This is very close to the average rate of inflation for Sydney over the 2004-2014 period which equalled 2.6 percent. It is also the middle of the Reserve Bank of Australia's inflation target (which is 2-3 percent).

g is the expected real capital gain. The expected real capital gain in year t is assumed to equal the geometric average of the real capital gain over the preceding x years. We consider four different values of x (i.e., 0, 10, 20 and 30 years). The first of these – x=0 – corresponds to when capital gains are excluded. More precisely, for cases where $x > 0$, the expected real capital gain in year t is calculated as follows:

$$\text{Expected real capital gain}_t = \left(\frac{EHPI_t / CPI_t}{EHPI_{t-x} / CPI_{t-x}} \right)^{1/x} - 1.$$

Here $EHPI_t$ is the level of the Established House Price Index and CPI_t is the level of the consumer price index for Sydney in year t. Both the EHPI and CPI are computed by the

[16] Fox and Tulip include repair costs as part of running costs. In our setup, we exclude repair costs from running costs since they are included in gross depreciation.

Australian Bureau of Statistics (ABS).[17]

Annualized expected real capital gains based on extrapolating over 10, 20 and 30 year horizons are shown in Table III. Diewert (2009), citing evidence on the length of housing booms and busts from Girouard et al. (2006), argues that a longer time horizon (e.g., 20 years) is more plausible in terms of how market participants form their expectations (see also Bracke 2013).

Insert Table III Here

Also shown in Table III are the implied values of the per dollar user cost u_t. The number of years over which expected real capital gains are extrapolated plays a pivotal role in determining the value of u_t. The volatility of per dollar user cost when expected capital gains are extrapolated from past performance over short time horizons has been noted previously by Verbrugge (2008), Garner and Verbrugge (2009), and Diewert (2009). We restrict the per dollar user cost to be nonnegative. This constraint is binding for u(10) in 2004 and 2005.

4.6 Computing average OOH expenditures

The 16th series of the Australian CPI uses expenditure weights derived from the 2009-2010 household expenditure survey (see Australian Bureau of Statistics 2011). Average expenditures ($y_{t,n}$) in Australian dollars for each component n of the CPI are provided for Sydney for the June quarter 2011 (here denoted by t).

Corresponding average expenditures ($y_{s,n}$) for heading n in other quarters s can be obtained as follows:

$$y_{s,n} = y_{t,n} \times \left(\frac{p_{s,n}}{p_{t,n}} \right),$$

where $p_{t,n}$ is the price index for heading n in the CPI in quarter t. In this way we are able to construct average OOH-acquisitions expenditures for Sydney for each quarter.

[17] The Established House Price Index (EHPI) is computed using the stratified-median approach, which may fail to fully adjust for quality changes over time. Given the EHPI is probably the most widely followed house price index for Sydney, it nevertheless is a useful benchmark for describing expectations of capital gains. The EHPI only goes back to 1986. To obtain prices back to 1984 or 1974 (for the cases where x=20 or 30), the EHPI was spliced together with an index calculated by Abelson and Chung (2005).

From (3) it can be seen that to compute average household expenditure on OOH according to the user cost method what is needed is estimates of the value of the average dwelling $\bar{P}_t$ (see Table I), the per dollar user cost u_t (see Table III), and an estimate of the share of households that are owner occupiers (i.e., H_t^{OOH}/H_t). In Sydney about two-thirds of households are owner-occupiers and one-third are renters (Australian Bureau of Statistics, Census of Population and Housing). It follows that $\bar{P}_t u_t$ should be multiplied by 2/3 to make it representative of the whole population of households. Combining these estimates generates the average (user cost) OOH expenditures in Australian dollars shown in Appendix C, Table C2, and expenditure shares shown in Table IV.

Similarly, from (1), to compute average household expenditure on OOH according to the rental equivalence method, what is needed is estimates of the average rent $\bar{R}_t$ (see Table I), and an estimate of H_t^{OOH}/H_t. The resulting rental equivalence OOH expenditure shares are also shown in Table IV. Again see Table C1 for the OOH expenditures in Australian dollars.

4.7 Average OOH expenditure shares compared

Average OOH expenditures and the corresponding expenditure shares are shown, respectively, in Appendix C, Table C2 and in Table IV for the following methods:

(i) User cost excluding real capital gains: u(0)
(ii) User cost with expected real capital gains extrapolated from the previous 10 years: u(10)
(iii) User cost with expected real capital gains extrapolated from the previous 20 years: u(20)
(iv) User cost with expected real capital gains extrapolated from the previous 30 years: u(30)
(v) Rental equivalence
(vi) Acquisitions

Insert Table IV Here

The OOH expenditure share under the acquisitions approach is derived from the 2009-2010 household expenditure survey. For this reason it stays fixed throughout our sample period.[18]

[18] The previous survey was undertaken in 2003-2004. We could have combined the weights from the two surveys in some way. But we decided simply to use the most recent weights for the whole sample.

It is noticeable in Table IV that the user cost approach excluding expected real capital gains, $u(0)$, has the largest OOH expenditure shares. The zero values for u(10) in 2004 and 2005 are due to the housing boom that started in about 1992 and ended in 2004. In both cases, the user cost would be negative if we did not impose a nonnegativity constraint. The implication is that in 2004, under $u(10)$ households expected very high real capital gains, and this acted to push down the user cost at the beginning of our sample period.

Rental equivalence generates higher OOH expenditure shares than $u(10)$, $u(20)$, $u(30)$. The reason $u(0)$ is higher than $u(10)$, $u(20)$, $u(30)$ is that the Sydney housing market has performed strongly since the 1970s. A sustained high level of capital gains generates an expectation of capital gains which acts to push down the user cost OOH expenditure share when expected capital gains are included. It is also noticeable that the acquisitions OOH expenditure level are lower than their user cost and rental equivalence counterparts. This is because the acquisitions approach focuses on only new residential construction and furthermore excludes the land component.

Coefficients of variation (CV) are included in Table IV so that the volatility of the OOH weights over time can be compared. Lengthening the expectation formation horizon acts to reduce the CV of the user cost OOH shares, although not as much as excluding capital gains completely. The CV of the OOH shares under rental equivalence is lower than for all versions of user cost.

The average OOH expenditure share for u(0) in Table IV is 29.2 percent, which is quite high compared say with the estimates for Canada provided by Sabourin and Dugay (2015). But as the following quote from the Guardian newspaper makes clear, housing costs are especially high in Sydney. (Note: Sydney is the capital of New South Wales.)

> [T]he Sydney housing market is as unaffordable as any time over the past 26 years. As of December 2016, 42% of the average disposable income of a New South Wales household was swallowed up by monthly mortgage payments on a median-priced house in the capital – after a 25% deposit. (Joshua Robertson in the Guardian on 3rd May, 2017)

The average OOH expenditure share for u(0) for the whole of Australia would be somewhat lower. The OOH expenditure share equals $k\bar{P}u/(z + k\bar{P}u)$, where z denotes average non-OOH expenditure, and k is the share of households that are owner occupiers. Assuming that k and the per dollar user cost u are the same across the whole of Australia, any differences in OOH expenditure shares are driven by differences in average house prices $\bar{P}$ and z. A rough estimate of the corresponding OOH expenditure share for Australia under u(0) can be computed therefore by adjusting for differences in average prices $\bar{P}$ and total non-OOH expenditure z in Sydney and the rest of Australia. According to the Bendigo Bank-REIA Real Estate Market Facts website, the average dwelling in Australia cost only 73.6 percent of the average for Sydney (adjusted for the relative mix of transacted houses and units) in 2013.[19] Using data from SGS Economics and Planning (2014) combined with total population data, it can be calculated that per capita expenditure in Australia is only at 91.6 percent of the level in Sydney. Revising both $\bar{P}$ and z down accordingly, we obtain that the average OOH expenditure share during our sample period for Australia is about 24.9 percent, as compared with 29.2 percent in Sydney.

It should be noted further that Australia is not a typical country. According to the Annual Demographia International Housing Affordability Survey, housing affordability in Australia is worse than in Canada, Ireland, Japan, Singapore, UK, and USA (see Demographia 2017). By implication, the expenditure share of OOH under u(0) would typically be lower than 24.9 percent in most countries.

4.8 The impact of OOH on the CPI

The 16th series of the Australian CPI is computed using a Laspeyres-type price index formula as follows:[20]

$$\frac{CPI_{t+1}}{CPI_t} = \sum_{n=1}^{N} \left[s_{b,n} \left(\frac{p_{t+1,n}}{p_{t,n}} \right) \right],$$

[19]See https://reia.asn.au/media-release/bendigo-bankreia-real-estate-market-facts/.

[20]More precisely, when the weights are fixed, this price index formula is referred to as a Young index (see chapter 1 of the Consumer Price Index Manual 2004).

where CPI_{t+1}/CPI_t is the change in the CPI from period t to $t+1$, $s_{b,n}$ denotes the expenditure weight for heading n in the base period which here is June 2011.

Under the acquisitions approach, OOH consists of three headings:

New dwelling purchase of owner occupiers,

Maintenance and repair of the dwelling,

Property rates and charges.

Here we will classify these headings for notational convenience as $N-2$, $N-1$, and N. To determine the impact on the CPI of switching from acquisitions to user cost or rental equivalence, it is necessary to separate the OOH components of the CPI from the rest of it, as follows:

$$\left.\frac{CPI_{t+1}}{CPI_t}\right| OOH = \left(\frac{1}{\sum_{n=1}^{N-3} s_{b,n}}\right) \sum_{n=1}^{N-3} \left[s_{b,n} \left(\frac{p_{t+1,n}}{p_{t,n}}\right)\right]$$
$$= \left(\frac{1}{\sum_{n=1}^{N-3} s_{b,n}}\right) \left[\frac{CPI_{t+1}}{CPI_t} - s_{b,N-2}\left(\frac{p_{t+1,N-2}}{p_{t,N-2}}\right) - s_{b,N-1}\left(\frac{p_{t+1,N-1}}{p_{t,N-1}}\right) - s_{b,N}\left(\frac{p_{t+1,N}}{p_{t,N}}\right)\right].$$

Our variants on the official CPI are then calculated as follows:

$$\frac{CPI^*_{t+1}}{CPI^*_t} = \left(\frac{1-s^*_{t,N+1}}{\sum_{n=1}^{N-3} s_{b,n}}\right) \sum_{n=1}^{N-3} \left[s_{b,n} \left(\frac{p_{t+1,n}}{p_{t,n}}\right)\right] + s^*_{t,N+1}\left(\frac{p^*_{t+1,N+1}}{p^*_{t,N+1}}\right),$$

where $s^*_{t,N+1}$ and $p^*_{t+1,N+1}/p^*_{t,N+1}$ are expenditure shares and price relatives for OOH obtained using either rental equivalence or user cost. It should be noted that in the case of rental equivalence and user cost, OOH is represented by a single heading here denoted by $N+1$, while under acquisitions it is represented by the three headings $N-2$, $N-1$, and N.

In addition to the official Australian acquisitions method, we provide results computed using the Eurostat version of acquisitions. The Australian and Eurostat methods use the same expenditure shares. They differ in the price index used for the heading *New dwelling purchase of owner occupiers*. As was explained in section 2.1, the Australian index uses a cost index of residential construction building materials. The Eurostat-type index uses an actual house price index. Ideally this index should cover only newly built dwellings. We are unable to do this for Sydney since in our data set we cannot distinguish new from existing dwellings.

Over our sample period the average inflation in house prices was 4.95 percent (see Table II). The corresponding inflation rate when OOH is excluded was 2.63 percent (see Table V). Hence real house prices rose by on average 2.32 percentage points per year.

The impact on the Sydney CPI of each approach to including OOH is shown in Table V. According to the official CPI – computed using the acquisitions method – the average annual inflation rate over our sample period is 2.70 percent. When OOH is completely excluded from the CPI, the average annual inflation rate is 2.63 percent. Hence the impact of OOH on the CPI is minimal, when the Australian version of the acquisitions approach is used. It pushes up the average by only 0.07 percentage points even, though the Sydney housing market experienced a significant boom during this period. This is because the house price index used by the Australian version of the acquisitions approach focuses on building costs, and it is land prices that have risen in Sydney. The Eurostat version of the acquisitions method is slightly more responsive to OOH, generating an average annual inflation rate of 2.86 percent.

Our preferred method for including OOH – $u(0)$ – generates an average annual inflation rate of 3.17 percent. In this case, including OOH using u(0) pushes up the CPI on average by 0.54 percentage points per year. Indeed all our alternative estimates, based on any of user cost, rental equivalence, or Eurostat-type acquisitions, are higher than the official CPI. Rental equivalence generates the highest CPI of 3.28 percent. This is due to the rental index rising faster than the house price index over our sample period as shown in Table II and Figure I.

Regarding the issue of downward bias in the CPI when capital gains are included in the user cost of OOH, it can be seen that average inflation under $u(10)$, $u(20)$ and $u(30)$ is lower than under $u(0)$. For Sydney, the longer the time horizon over which expectations are extrapolated, the lower is the resulting CPI. This is due to the strong performance of the Sydney housing market in the decades prior to the start of our data set. In general, we would normally expect a smaller bias when expectations are extrapolated over longer time horizons.

Insert Table V Here

5 Some Implications of the Treatment of OOH

5.1 The impact on the CPI of excluding OOH when real house prices are rising

We compute average annual rates of appreciation of real house prices over the periods 1950-2012, 1980-2012, and 2000-2012 for 14 OECD countries using data provided by Knoll, Schularick and Steger (2017). The results are presented in Table VI. In every country in each of these periods (with one minor exception) real house prices rose.[21]

Insert Table VI Here

To assess the impact of excluding OOH from the CPI, in the presence of real house price appreciation in the range observed in Table VI, we undertake a simulation calibrated to our Australian data set.

Adopting u(0) as our benchmark for including OOH in the CPI, we can estimate the downward bias in the CPI that results from excluding OOH under different rates of appreciation of real house prices. A faster appreciation in house prices affects both the OOH price index and expenditure share. To determine the affect on the CPI it is first useful to separate the CPI into its OOH and non-OOH (denoted by C) components as follows:

$$CPI_{t,t+1} = s_{t,C}\left(\frac{p_{t+1,C}}{p_{t,C}}\right) + s_{t,OOH}\left(\frac{p_{t+1,OOH}}{p_{t,OOH}}\right). \tag{11}$$

Next we set $p_{t+1,OOH}/p_{t,OOH} = (1+\lambda)(p_{t+1,C}/p_{t,C})$, where λ denotes the rate of real house price appreciation. The expenditure shares of non-OOH $s_{t,C}$ and OOH $s_{t,OOH}$ are:

$$s_{t,C} = \frac{z_t}{k\bar{P}_t u_t + z_t}, \quad s_{t,OOH} = \frac{k\bar{P}_t u_t}{k\bar{P}_t u_t + z_t},$$

where z_t is per capita non-OOH expenditure in period t, and $k\bar{P}_t u_t$ is per capita expenditure on OOH. Per dollar user cost u_t is computed according to u(0), i.e., excluding capital gains. We assume here that the share of owner occupiers k in the population remains fixed, and that

[21] The unusually rapid increase in house prices in France since 1950 can be placed in context by noting that house prices in 1950 were far lower than in 1914. So part of this rise can be interpreted as a recovery from the disruptions caused by two world wars.

the average price $\bar{P}_t$ rises at the same rate as the house price index.

$$\bar{P}_{t+1} = (1 + \lambda) \left(\frac{p_{t+1,C}}{p_{t,C}} \right) \bar{P}_t \tag{12}$$

Similarly, z_t is assumed to rise at the average annual rate of growth of per capita nominal GDP:

$$z_{t+1} = (1 + rgdp) \left(\frac{p_{t+1,C}}{p_{t,C}} \right) z_t, \tag{13}$$

where $rgdp$ is the real growth rate of per capita GDP.

Taking Australia as our benchmark for the period 2004-2014, we set $p_{t+1,C}/p_{t,C}$ according to the CPI excluding OOH in the final column of Table V. The initial value of $k\bar{P}_t u_t$ is set to our estimate of the Australian average in 2004, \$1547.4, and the initial value of z_t likewise to the Australian average, \$4672.4.[22] We take the actual values of u_t from Table III. The initial value of $\bar{P}$ is obtained residually given the initial values of $k\bar{P}_t u_t$, k and u_t. Each period, $\bar{P}$ and z are then updated according to (12) and (13). All that remains is to select values for $rgdp$ and λ. $rgdp$ is set equal to the average annual growth rate of real per capita GDP over the period 2004-2014 in Australia.

Real appreciation rates of house prices in Table VI lie in the range -1 to 6 percent per year. Varying the rate of real appreciation of house prices λ in this range generates the results shown in Table VII. Excluding OOH generates a downward bias in the CPI whenever real house prices rise (i.e., $\lambda > 0$). When real house prices rise by 1 percent per year, including OOH using u(0) would increase the CPI by 0.22 percentage points per year, and by 2.23 percentage points over 10 years. When real house prices rise by 6 percent per year, including OOH raises the CPI by 1.55 percentage points per year and by 16.65 percentage points over 10 years.

Insert Table VII Here

Given that real appreciation rates for housing of say 4 percentage points per year for sustained periods are not unusual in Table VI, the results in Table VII seem to indicate that the compounded impact on welfare of excluding OOH from the CPI could be huge. It should

[22] These values are derived from the OOH expenditure estimates in Appendix C, Table C2, with adjustments made to convert from Sydney to Australia as explained in section 4.7.

be noted, however, that our focus here is on the CPI as used in monetary policy, not welfare comparisons. We are not recommending the user cost method, u(0), for the indexation of wages and pensions.

5.2 Monetary policy

Inflation targeting has spread rapidly around the world since its introduction in New Zealand in 1990. Given that real house prices have typically been rising for many decades in the OECD (see Table VI), the treatment of OOH in the CPI could potentially have significant implications for monetary policy. Of particular interest in Table VI are the euro area countries, the UK, and Australia. The European Central Bank's target index for monetary policy – the HICP – excludes OOH. The Bank of England also targets the HICP. The way OOH is included in the Australian CPI makes is almost equivalent to excluding it completely.

For these countries, our results indicate that the exclusion of OOH is causing a downward bias in the CPI. If this is not factored into the inflation target then the implication is that monetary policy will be too loose.

Within this inflation targeting framework, there has been much debate, particularly since the global financial crisis (GFC), over whether central banks should also respond to movements in house prices when setting monetary policy. The perspective that central banks should raise interest rates in response to a booming housing market (or stock market) is known as "leaning against the wind". It is argued that leaning against the wind is particularly important during housing booms, since such booms are almost invariably credit driven. Any subsequent bust therefore could inflict significant damage on the banking sector (see Cecchetti 2006 and Mishkin 2011).

More recently, however, Svensson (2016) has argued that raising interest rates during an asset market boom can make matters worse by raising the real value of household debt and weakening the economy. Svensson goes further and recommends doing the opposite, "leaning with the wind", preferably combined with tighter macroprudential regulation (e.g., restrictions on loan-to-value and debt-to-income ratios).

We do not wish to take a stance here on this "leaning" debate. Our point is that most of the participants in this debate (Cecchetti being an exception) are neglecting an important issue, which is the extent to which the CPI already responds to movements in house prices. This depends on how OOH is treated in the CPI.

Countries, such as Canada and Sweden which use versions of u(0), already implicitly engage in a certain degree of leaning against the wind. This may be one reason why Svensson (2016) finds that explicit leaning against the wind (i.e., over and above that already implied by using u(0)) in Sweden has been suboptimal in recent years.

6 Conclusion

The CPI is sensitive to the way OOH expenditures and prices are measured. On conceptual grounds we have argued that the user cost approach should be the preferred method for including OOH in a CPI used for monetary policy purposes. In this context, we recommend excluding capital gains from the user cost formula. Also, a long-term interest rate should be used, to reduce the immediate sensitivity of the CPI to changes in monetary policy. If necessary the natural rate of interest could be used instead (see Summers 2016). Given these adjustments the user cost method is relatively straightforward to implement.

The user cost method should produce more internationally comparable results than the acquisitions method, where residential construction, the proportion of self-builds and the recording thereof, can vary hugely across countries. Similarly, rental equivalence may not be feasible for countries with small or highly regulated rental markets. This is particularly an issue for the EU, where the size of rental markets vary significantly while at the same time there is a requirement that all countries treat OOH in the same way in the HICP.

Applying hedonic quantile-regression methods to microdata for Sydney over the years 2004-2014 we are able to impute prices and rents across different quantiles of the price and rent distributions. Using these imputations, we estimate the impact of a number of different treatments of OOH on the CPI.

For Sydney, the baseline CPI, excluding OOH over our sample period, is on average 2.6

percent. When OOH is included, using our preferred user cost method, which excludes capital gains, the average CPI increases to 3.2 percent.

More generally, the size of the downward bias in the CPI resulting from excluding OOH depends on how fast real house prices are rising. In Sydney, over our sample period, real house prices rose by a bit over 2 percent per year. Many OECD countries have experienced similar rates of real house price appreciation since the 1950s. For countries that exclude OOH from their CPIs – the HICP in Europe being a case in point – a downward bias of about half a percent per year may therefore not be uncommon.

Furthermore, given that a housing boom will act to push up the CPI under our preferred treatment of OOH, it follows that an inflation targeting central bank will naturally engage in some "leaning against the wind" during a housing boom. The case for active "leaning" in response to a housing boom, therefore, depends on how OOH is treated in the CPI.

In conclusion, more research is needed in the monetary policy literature on the treatment of OOH in the CPI, and how this affects the choice of inflation target, and the debate over leaning against or with the wind.

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Table I: Average Imputed Prices and Rents in Australian Dollars

	OOH			Rents (weekly)		
Year	Houses	Units	Total	Houses	Units	Total
2004	707 196	439 876	607 312	393.1	319.3	350.8
2005	685 918	436 526	592 732	404.9	328.4	361.0
2006	695 589	437 966	599 328	422.6	344.2	377.6
2007	742 069	454 911	634 772	459.4	376.8	412.0
2008	738 305	457 780	633 487	517.9	420.5	462.1
2009	762 267	478 329	656 173	514.5	432.2	467.3
2010	840 667	531 912	725 300	562.5	461.1	504.4
2011	830 637	542 368	722 925	595.4	489.2	534.5
2012	830 048	553 450	726 697	607.3	502.2	547.0
2013	920 854	605 285	802 941	622.3	515.0	560.8
2014	1 069 613	689 015	927 402	642.9	530.5	578.5

Notes: The table reports the mean sales price for OOH and the mean weekly rent separately for houses, units, and the total market (i.e., houses and units combined). Results are obtained from imputations based on conditional quantile models (see Appendix B).

Table II: Price and Rent Indexes

	PRICE INDEXES			RENT INDEXES		
	Houses	Units	Total	Houses	Units	Total
2004	1.000	1.000	1.000	1.000	1.000	1.000
2005	0.964	0.987	0.973	1.026	1.027	1.027
2006	0.968	0.985	0.975	1.071	1.071	1.071
2007	1.022	1.022	1.022	1.163	1.175	1.170
2008	1.008	1.044	1.022	1.377	1.312	1.340
2009	1.071	1.109	1.086	1.392	1.353	1.370
2010	1.198	1.232	1.212	1.540	1.452	1.488
2011	1.208	1.265	1.231	1.642	1.546	1.586
2012	1.223	1.287	1.248	1.692	1.594	1.634
2013	1.362	1.402	1.379	1.753	1.642	1.687
2014	1.600	1.588	1.598	1.828	1.697	1.750
Average Rise						
Per Year	5.005%	4.834%	4.949%	6.325%	5.474%	5.818%

Notes: Results are based on the Törnqvist price index formula. We use imputed prices and rents from conditional quantile models (see Appendix B). The overall price (rent) indexes are computed by taking weighted geometric means of the house and unit price (rent) relatives, with the weights each period determined by the number of house and unit transactions in that same period.

Table III: Expected Real Capital Gains and Per Dollar User Costs: Sydney 2004-2014

	$g(0)$	$g(10)$	$g(20)$	$g(30)$	r	$u(0)$	$u(10)$	$u(20)$	$u(30)$
2004	0.0000	0.0660	0.0501	0.0331	0.0585	0.0635	0.0000	0.0133	0.0303
2005	0.0000	0.0591	0.0476	0.0335	0.0514	0.0564	0.0000	0.0088	0.0229
2006	0.0000	0.0555	0.0436	0.0328	0.0574	0.0624	0.0069	0.0188	0.0295
2007	0.0000	0.0533	0.0449	0.0345	0.0620	0.0670	0.0138	0.0221	0.0326
2008	0.0000	0.0481	0.0415	0.0354	0.0659	0.0709	0.0228	0.0293	0.0355
2009	0.0000	0.0338	0.0184	0.0301	0.0556	0.0606	0.0268	0.0422	0.0305
2010	0.0000	0.0393	0.0312	0.0293	0.0533	0.0583	0.0190	0.0271	0.0290
2011	0.0000	0.0400	0.0327	0.0262	0.0516	0.0566	0.0166	0.0239	0.0304
2012	0.0000	0.0217	0.0300	0.0274	0.0300	0.0350	0.0132	0.0050	0.0075
2013	0.0000	0.0071	0.0305	0.0312	0.0354	0.0404	0.0333	0.0099	0.0092
2014	0.0000	0.0067	0.0359	0.0354	0.0370	0.0420	0.0353	0.0061	0.0066
Average	0.0000	0.0391	0.0369	0.0317	0.0507	0.0557	0.0171	0.0188	0.0240

Notes: In the per dollar user cost formula we hold depreciation fixed at $\delta = 0.011$, running and average transaction costs fixed at $\omega = 0.019$, and expected inflation fixed at $\pi = 0.025$. r is the yield on 10-year government bonds. $g(x)$ is the expected real capital gain and $u(x)$ the per dollar user cost obtained by extrapolating expectations of capital gains over an x year time horizon. The per dollar user cost is calculated using the formula in (2). u(0) excludes capital gains.

Table IV: Average Monthly OOH Expenditure Shares: Sydney 2004-2014

	$u(0)$	$u(10)$	$u(20)$	$u(30)$	Rental Equiv.	Acquis.
2004	0.3246	0.0000	0.0919	0.1870	0.1859	0.1198
2005	0.2866	0.0000	0.0590	0.1402	0.1846	0.1198
2006	0.3071	0.0466	0.1177	0.1737	0.1894	0.1198
2007	0.3324	0.0926	0.1413	0.1947	0.2010	0.1198
2008	0.3354	0.1395	0.1730	0.2016	0.2132	0.1198
2009	0.3034	0.1614	0.2327	0.1797	0.2109	0.1198
2010	0.3100	0.1276	0.1727	0.1826	0.2186	0.1198
2011	0.2969	0.1102	0.1513	0.1849	0.2235	0.1198
2012	0.2050	0.0890	0.0352	0.0528	0.2247	0.1198
2013	0.2414	0.2078	0.0723	0.0676	0.2230	0.1198
2014	0.2686	0.2359	0.0508	0.0547	0.2215	0.1198
Average	0.2920	0.1101	0.1180	0.1472	0.2087	0.1198
CV	0.1370	0.6931	0.5254	0.4024	0.0758	0.0000

Table V: CPI Annual Inflation for Sydney

	$u(0)$	$u(10)$	$u(20)$	$u(30)$	Rent Eq.	Acq(AUS)	Acq(EUR)	OOH Excl.
2004-05	0.617%	2.215%	1.763%	1.295%	2.298%	2.463%	1.820%	2.215%
2005-06	3.012%	4.146%	3.912%	3.591%	4.179%	3.846%	3.791%	4.146%
2006-07	2.709%	1.890%	2.114%	2.289%	3.166%	1.736%	2.078%	1.744%
2007-08	2.850%	3.873%	3.666%	3.438%	6.331%	4.323%	3.869%	4.269%
2008-09	2.785%	1.766%	1.940%	2.089%	1.300%	1.309%	1.600%	1.041%
2009-10	5.485%	4.249%	4.869%	4.409%	4.060%	2.906%	3.609%	2.845%
2010-11	3.106%	3.515%	3.414%	3.392%	4.398%	3.766%	3.604%	3.800%
2011-12	1.316%	1.284%	1.291%	1.297%	1.671%	1.310%	1.313%	1.266%
2012-13	4.046%	3.113%	2.680%	2.821%	2.585%	2.587%	3.149%	2.396%
2013-14	5.797%	5.349%	3.546%	3.483%	2.831%	2.813%	3.761%	2.538%
Average	3.172%	3.140%	2.920%	2.810%	3.282%	2.706%	2.859%	2.630%
CV	0.483	0.397	0.369	0.351	0.432	0.370	0.361	0.413

Notes: u(0) denotes the user cost method with capital gains excluded. u(x) denote the user cost method with expected capital gains extrapolated based on the preceding x years. Rent Eq. denotes the rental equivalence method. Acq(AUS) and Acq(EUR) denote respectively the Australian and Eurostat versions of the acquisitions method. OOH Excl. denotes the CPI with OOH excluded.

Table VI: Average Annual Increase in Real House Prices

	1950-2012	1980-2012	2000-2012
Australia	2.35%	2.94%	4.45%
Belgium	2.45%	2.03%	3.69%
Canada	2.71%	2.42%	5.00%
Switzerland	1.00%	1.20%	3.67%
Denmark	1.75%	1.12%	1.32%
Finland	3.31%	2.45%	2.70%
France	5.08%	2.05%	4.78%
Great Britain	2.28%	2.78%	3.22%
Netherlands	2.61%	1.69%	-0.01%
Norway	2.39%	4.17%	5.51%
Sweden	1.51%	2.16%	5.12%
USA	0.30%	0.28%	0.01%

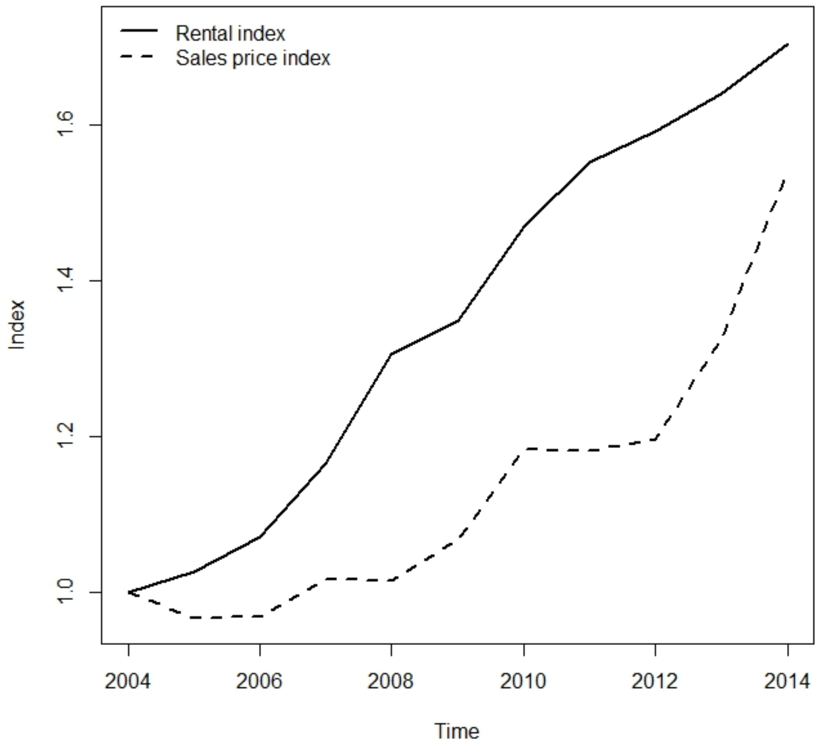
Source: Knoll, Schularick and Steger (2017), online additional materials "Data Set" available on the American Economic Review website.

Table VII: Impact of Including OOH in the CPI Using u(0)

	1 year Difference	10 year Difference
λ=-1%	-0.207%	-2.050%
λ=0%	0.000%	0.000%
λ=1%	0.221%	2.230%
λ=2%	0.456%	4.654%
λ=3%	0.706%	7.290%
λ=4%	0.972%	10.155%
λ=5%	1.254%	13.267%
λ=6%	1.552%	16.648%

Notes: λ denotes the rate at which real house prices are rising. The "Difference" here measures the impact of including OOH in the CPI using the user cost method, u(0). For example, when $\lambda = 3\%$, it follows that the CPI is 0.706 percentage points higher under the u(0) method than if OOH is excluded from the CPI.

Figure I: Rental and sales prices indexes.



Notes: Results are based on the chained Törnqvist price index formula. We use imputed prices and rents from conditional quantile models (see Appendix B).

Appendix: For Online Publication

A The Treatment of Capital Gains in the User Cost of OOH: A Cause of Bias in the CPI?

A.1 A thought experiment

Suppose house prices rise and then return back to their original level. Suppose further that during this process everything else in the economy – prices and expenditure on all goods and services and all the components of user cost except capital gains – remains fixed.

This appendix explores the impact of such a scenario on the CPI when OOH is included using the user cost method with capital gains included either ex post or ex ante.

From an axiomatic perspective the CPI should return to its original value. We show that this does not happen. The exact outcome depends both on how capital gains are included in user cost, and on the number of periods included in the comparison. Our overall conclusions are summarized at the end.

A.2 A numerical example

Suppose that house prices rise by 4 percent per period for 4 years before then falling by 4 percent per period for four periods. The initial price of a representative house in period 1 is \$200 000. Normalizing the price index to 1 in period 1, house prices peak in period 5 at 1.16986, before falling back to 1 by period 9. It is assumed that the prices of all other components of the CPI (except OOH) remain constant, and that the total non-OOH expenditure remains fixed at \$90 000. Finally, it is also assumed that all components of per dollar user cost except capital gains remain constant and that these components sum to 0.05. This numerical example is constructed to make sure that in all cases considered the user cost never goes negative.

For this example, in Table A1, we show the impact on the CPI (as measured by a Fisher price index) of alternative treatments of capital gains on OOH in a user cost setting. The following cases are considered: capital gains are excluded as defined in (6); capital gains are included ex post as defined in (5); capital gains are included ex ante as defined in (7). With regard to the latter we consider the cases where expectations are extrapolated over a 1, 4 and 8 year horizon. These results are then summarized in Table A2, which also includes all possible ex ante expectation horizons ranging from 1 to 8 years.

From an axiomatic perspective, the chained Fisher price index calculated over the full nine periods should equal 1. This is the result obtained in Tables A1 and A2 when either real capital gains are excluded or when they are included ex ante with expectations extrapolated over the previous eight years (coinciding with the price cycle). When expected real capital gains are extrapolated over a shorter time horizon or if they are included ex post, then the chained Fisher price index ends up below 1, implying a downward bias in the CPI. From Table A2 it can be seen that the size of this bias gets bigger as the time horizon over which expectations are extrapolated gets smaller. The biggest bias though occurs when real capital gains are included ex post.

A.3 An algebraic analysis of the three period case

The Laspeyres price index formula can be written as follows:

$$\text{Laspeyres}: \quad CPI_{12}^{L} = \sum_{n=1}^{N} s_{1n}\left(\frac{p_{2n}}{p_{1n}}\right), \quad CPI_{23}^{L} = \sum_{n=1}^{N} s_{2n}\left(\frac{p_{3n}}{p_{2n}}\right),$$

where s_{1n} and s_{2n} are the expenditure share of heading n in periods 1 and 2 respectively. Here heading 1 is OOH. All other headings are combined and denoted by heading 2. OOH expenditure under the user cost approach in period t is given by $P_t u_t$.

We now make four assumptions.

(i) The expenditure on heading 2 (i.e., all other expenditure) remains constant and takes the value z^*.

(ii) The fraction of households that are owner-occupiers – denoted by o – remains constant over time. For example if $o = 0.6$ this means that 60 percent of households are owner-occupiers.

(iii) Let P_t and P_{t+1} denote the average house price in periods t and $t+1$ respectively. It is assumed that the house price index between periods t and $t+1$ can be written as the

Table A1: Example of the Impact of the Treatment of Real Capital Gains on the CPI

Excluding capital gains							
Year	HPI	g	u	Pu	Other Exp	OOH Weight	Fisher
1	1.000	NA	0.050	10000	90000	0.1000	1.000
2	1.040	NA	0.050	10400	90000	0.1036	1.004
3	1.082	NA	0.050	10816	90000	0.1073	1.004
4	1.125	NA	0.050	11249	90000	0.1111	1.004
5	1.170	NA	0.050	11699	90000	0.1150	1.004
6	1.125	NA	0.050	11249	90000	0.1111	0.996
7	1.082	NA	0.050	10816	90000	0.1073	0.996
8	1.040	NA	0.050	10400	90000	0.1036	0.996
9	1.000	NA	0.050	10000	90000	0.1000	0.996
Chained price index comparing years 1 and 9							1.000
Including ex post capital gains							
Year	HPI	g	u	Pu	Other Exp	OOH Weight	Fisher
1	1.000	0.040	0.010	2000	90000	0.0217	1.000
2	1.040	0.040	0.010	2080	90000	0.0226	1.001
3	1.082	0.040	0.010	2163	90000	0.0235	1.001
4	1.125	0.040	0.010	2250	90000	0.0244	1.001
5	1.170	-0.038	0.088	20697	90000	0.1870	1.004
6	1.125	-0.038	0.088	19901	90000	0.1811	0.993
7	1.082	-0.038	0.088	19136	90000	0.1753	0.993
8	1.040	-0.038	0.088	18400	90000	0.1697	0.993
9	1.000	0.000	0.050	10000	90000	0.1000	0.995
Chained price index comparing years 1 and 9							0.981
Including ex ante capital gains (expectations extrapolated over 1 year horizon)							
Year	HPI	g	u	Pu	Other Exp	OOH Weight	Fisher
1	1.000	0.000	0.050	10000	90000	0.1000	1.000
2	1.040	0.040	0.010	2080	90000	0.0226	1.002
3	1.082	0.040	0.010	2163	90000	0.0235	1.001
4	1.125	0.040	0.010	2250	90000	0.0244	1.001
5	1.170	0.040	0.010	2340	90000	0.0253	1.001
6	1.125	-0.038	0.088	19901	90000	0.1811	0.996
7	1.082	-0.038	0.088	19136	90000	0.1753	0.993
8	1.040	-0.038	0.088	18400	90000	0.1697	0.993
9	1.000	-0.038	0.088	17692	90000	0.1643	0.993
Chained price index comparing years 1 and 9							0.981

Table A1: Example of the Impact of the Treatment of Real Capital Gains on the CPI (continued)

Including ex ante capital gains (expectations extrapolated over 4 year horizon)							
Year	HPI	g	u	Pu	Other Exp	OOH Weight	Fisher
1	1.000	0.000	0.050	10000	90000	0.1000	1.000
2	1.040	0.010	0.040	8350	90000	0.0849	1.004
3	1.082	0.020	0.030	6532	90000	0.0677	1.003
4	1.125	0.030	0.020	4533	90000	0.0479	1.002
5	1.170	0.040	0.010	2340	90000	0.0253	1.001
6	1.125	0.020	0.030	6793	90000	0.0702	0.998
7	1.082	0.000	0.050	10816	90000	0.1073	0.997
8	1.040	-0.019	0.069	14439	90000	0.1383	0.995
9	1.000	-0.038	0.088	17692	90000	0.1643	0.994
Chained price index comparing years 1 and 9							0.994

Including ex ante capital gains (expectations extrapolated over 8 year horizon)							
Year	HPI	g	u	Pu	Other Exp	OOH Weight	Fisher
1	1.000	0.000	0.050	10000	90000	0.1000	1.000
2	1.040	0.005	0.045	9378	90000	0.0944	1.004
3	1.082	0.010	0.040	8685	90000	0.0880	1.004
4	1.125	0.015	0.035	7915	90000	0.0808	1.003
5	1.170	0.020	0.030	7065	90000	0.0728	1.003
6	1.125	0.015	0.035	7915	90000	0.0808	0.997
7	1.082	0.010	0.040	8685	90000	0.0880	0.997
8	1.040	0.005	0.045	9378	90000	0.0944	0.996
9	1.000	0.000	0.050	10000	90000	0.1000	0.996
Chained price index comparing years 1 and 9							1.000

Notes: In this example, house prices rise from period 1 to period 5 and then fall back to their original value by period 9.

Table A2: Summary of Results in Example Based on Fisher Price Index Formula

Treatment of Real	Level of the CPI in Given Period		
Capital Gains	CPI_1	CPI_5	CPI_9
Excluded	1.0000	1.0170	1.0000
Ex post	1.0000	1.0068	0.9808
Expected - 1 year	1.0000	1.0053	0.9810
Expected - 2 years	1.0000	1.0069	0.9854
Expected - 3 years	1.0000	1.0087	0.9898
Expected - 4 years	1.0000	1.0104	0.9942
Expected - 5 years	1.0000	1.0118	0.9974
Expected - 6 years	1.0000	1.0127	0.9991
Expected - 7 years	1.0000	1.0133	0.9998
Expected - 8 years	1.0000	1.0138	1.0000

Notes: In this example, house prices rise from period 1 to period 5 and then fall back to their original value by period 9.

ratio of the average house prices in the two periods. Hence the house price index takes the following form: P_{t+1}/P_t.

(iv) The price of housing in period 3 is the same as in period 1 (i.e., $P_1 = P_3$). Defining μ as the growth rate of prices from period 1 to 2, it therefore follows that

$$\frac{P_2}{P_1} = 1 + \mu, \quad \text{and} \quad \frac{P_3}{P_2} = \frac{1}{1+\mu}.$$

We assume that $\mu > 0$.

It follows from assumptions (i) and (ii) that the expenditure shares for owner occupied housing (OOH) and everything else in periods 1, 2 and 3 are as follows:

$$\begin{aligned}
\text{Period 1}: \quad s_{11} &= \frac{oP_1u_1}{oP_1u_1 + z^*}, \quad s_{12} = \frac{z^*}{oP_1u_1 + z^*},\\
\text{Period 2}: \quad s_{21} &= \frac{oP_2u_2}{oP_2u_2 + z^*}, \quad s_{22} = \frac{z^*}{oP_2u_2 + z^*},\\
\text{Period 3}: \quad s_{31} &= \frac{oP_3u_3}{oP_3u_3 + z^*}, \quad s_{33} = \frac{z^*}{oP_3u_3 + z^*}.
\end{aligned}$$

Given these expenditure shares and assumptions (iii) and (iv), the Laspeyres formula reduces to

$$\begin{aligned}
CPI_{12}^L &= \left(\frac{oP_1u_1}{oP_1u_1 + z^*}\right)\left(\frac{P_2}{P_1}\right) + \frac{z^*}{oP_1u_1 + z^*} = \frac{oP_2u_1 + z^*}{oP_1u_1 + z^*},\\
CPI_{23}^L &= \left(\frac{oP_2u_2}{oP_2u_2 + z^*}\right)\left(\frac{P_1}{P_2}\right) + \frac{z^*}{oP_2u_2 + z^*} = \frac{oP_1u_2 + z^*}{oP_2u_2 + z^*}.
\end{aligned}$$

If we now define $z = z^*/o$, the Laspeyres formulas further simplify to the following:

$$\begin{aligned}
CPI_{12}^L &= \left(\frac{P_1u_1}{P_1u_1 + z}\right)\left(\frac{P_2}{P_1}\right) + \frac{z}{P_1u_1 + z} = \frac{P_2u_1 + z}{P_1u_1 + z},\\
CPI_{23}^L &= \left(\frac{P_2u_2}{P_2u_2 + z}\right)\left(\frac{P_1}{P_2}\right) + \frac{z}{P_2u_2 + z} = \frac{P_1u_2 + z}{P_2u_2 + z}.
\end{aligned}$$

Now we take the product of CPI_{12}^L and CPI_{23}^L:

$$CPI_{12}^L \times CPI_{23}^L = \left(\frac{P_2u_1 + z}{P_1u_1 + z}\right)\left(\frac{P_1u_2 + z}{P_2u_2 + z}\right) = 1 - \frac{z(u_2 - u_1)(P_2 - P_1)}{(P_1u_1 + z)(P_2u_2 + z)}$$

Similarly, the Paasche price index formula can be written as follows:

$$\text{Paasche}: \quad CPI_{12}^P = \left[\sum_{n=1}^{N} s_{2n}\left(\frac{p_{1n}}{p_{2n}}\right)\right]^{-1}, \quad CPI_{23}^P = \left[\sum_{n=1}^{N} s_{3n}\left(\frac{p_{2n}}{p_{3n}}\right)\right]^{-1}.$$

In an analogous way to Laspeyres, the chained Paasche price index can be written as:

$$CPI_{12}^P \times CPI_{23}^P = \left(\frac{P_2u_2 + z}{P_1u_2 + z}\right)\left(\frac{P_1u_3 + z}{P_2u_3 + z}\right) = 1 - \frac{z(u_3 - u_2)(P_2 - P_1)}{(P_1u_2 + z)(P_2u_3 + z)}.$$

Suppose now further that $P_2 > P_1$. In this case when $u_2 > u_1$ it follows that $CPI_{12}^L \times CPI_{23}^L < 1$. Furthermore, when $u_3 > u_2$ it follows that $CPI_{12}^P \times CPI_{23}^P < 1$.

$$u_2 > u_1 \Longleftrightarrow CPI_{12}^L \times CPI_{23}^L < 1, \tag{14}$$

$$u_3 > u_2 \Longleftrightarrow CPI_{12}^P \times CPI_{23}^P < 1. \tag{15}$$

Case 1: Capital gains are included ex post

The user cost of OOH when capital gains are included ex post is as follows:

$$u_1 = k - \left(\frac{P_2 - P_1}{P_1}\right) = k - \mu,$$
$$u_2 = k - \left(\frac{P_1 - P_2}{P_1}\right) = k + \mu,$$
$$u_3 = k,$$

where $k = r + \delta + \omega + \gamma - \pi$ (i.e., all the other components of user cost) is assumed to remain fixed. Hence all changes in u are caused by the treatment of capital gains. Hence $u_2 - u_1 = 2\mu > 0$, and because of (14)

$$CPI^L_{12} \times CPI^L_{23} < 1.$$

For Paasche we have that $u_3 - u_2 = -\mu < 0$ and hence because of (15)

$$CPI^P_{12} \times CPI^P_{23} > 1.$$

Conclusion: In the three-period case, when capital gains are included ex post, the chained Laspeyres CPI has a downward bias and the chained Paasche CPI an upward bias.

Case 2: Capital gains are included ex ante with expectations extrapolated from the previous period

When capital gains are included ex ante in the per dollar user cost, u_1, u_2 and u_3 take the following values:

$$u_1 = k,$$
$$u_2 = k - \left(\frac{P_2 - P_1}{P_1}\right) = k - \mu,$$
$$u_3 = k - \left(\frac{P_1 - P_2}{P_1}\right) = k + \mu.$$

Now for Laspeyres we obtain the reverse result that

$$CPI^L_{12} \times CPI^L_{23} = 1 - \frac{z(u_2 - u_1)(P_2 - P_1)}{(P_1 u_1 + z)(P_2 u_2 + z)} = 1 + \frac{P_1 \mu^2 z}{(P_1 u_1 + z)(P_2 u_2 + z)} > 1,$$

while for Paasche we obtain the same result as before:

$$CPI^P_{12} \times CPI^P_{23} = 1 - \frac{z(u_3 - u_2)(P_2 - P_1)}{(P_1 u_2 + z)(P_2 u_3 + z)} = 1 - \frac{2P_1 \mu^2 z}{(P_1 u_2 + z)(P_2 u_3 + z)} < 1.$$

Conclusion: In the three-period case, when capital gains are included ex ante, a chained Laspeyres CPI has an upward bias while a chained Paasche CPI has a downward bias.

A.4 An algebraic analysis of the general multi-period case

Suppose now we generalize this example to an arbitrary number of periods. Starting from period 1, house prices rise for M consecutive periods at the rate μ, after which prices then fall for M consecutive periods at the rate μ returning to their original value in period $1+2M$. Hence prices peak in period $M+1$. More precisely, for periods $t=1,\ldots,M$ we have that $P_{t+1}/P_t = 1+\mu$, while for periods $t=M+1,\ldots,2M$ we have that $P_{t+1}/P_t = 1/(1+\mu)$. It now follows that chained Laspeyres and Paasche price indexes can be written as follows:

$$\prod_{t=1}^{2M} CPI^L_{t,t+1} = \prod_{t=1}^{2M}\left(\frac{P_{t+1}u_t + z}{P_t + z}\right),$$
$$\prod_{t=1}^{2M} CPI^P_{t,t+1} = \prod_{t=1}^{2M}\left(\frac{P_{t+1}u_{t+1} + z}{P_{t+1} + z}\right).$$

Case 1: Capital gains are included ex post

When capital gains are included ex post the user cost of OOH in each period is as follows:

$$u_t = \begin{cases} k-\mu, & \text{for } 1 \le t \le M, \\ k+\mu, & \text{for } M+1 \le t \le 2M, \\ k, & \text{for } t = 2M+1. \end{cases}$$

It now follows for Laspeyres that

$$
\begin{aligned}
\prod_{t=1}^{2M} CPI^{L}_{t,t+1} =& \left(\frac{P_2 u_1 + z}{P_1 u_1 + z}\right)\left(\frac{P_3 u_2 + z}{P_2 u_2 + z}\right)\cdots\left(\frac{P_{M+1} u_M + z}{P_M u_M + z}\right) \\
&\cdot\left(\frac{P_{M+2} u_{M+1} + z}{P_{M+1} u_{M+1} + z}\right)\cdots\left(\frac{P_1 u_{2M} + z}{P_{2M} u_{2M} + z}\right) \\
=& \left(\frac{P_1 u_{2M} + z}{P_{2M+1} u_1 + z}\right)\left(\frac{P_{M+1} u_M + z}{P_{M+1} u_{M+1} + z}\right) \\
=& \left(\frac{P_1 (k+\mu) + z}{P_1 (k-\mu) + z}\right)\left(\frac{P_{M+1}(k-\mu) + z}{P_{M+1}(k+\mu) + z}\right) \\
=& \left(\frac{(k+\mu) + y}{(k-\mu) + y}\right)\left(\frac{(1+\mu)^M (k-\mu) + z}{(1+\mu)^M (k+\mu) + z}\right) \\
=& 1 - \frac{2\mu y[(1+\mu)^M - 1]}{[k-\mu+y][(1+\mu)^M (k+\mu) + y]} < 1,
\end{aligned}
$$

where $y = z/P_1$, and it is assumed that $k - \mu > 0$.

For Paasche we have that

$$
\begin{aligned}
\prod_{t=1}^{2M} CPI^{P}_{t,t+1} =& \left(\frac{P_2 u_2 + z}{P_1 u_2 + z}\right)\left(\frac{P_3 u_3 + z}{P_2 u_3 + z}\right)\cdots\left(\frac{P_M u_M + z}{P_{M-1} u_M + z}\right) \\
&\cdot\left(\frac{P_{M+1} u_{M+1} + z}{P_M u_{M+1} + z}\right)\cdots\left(\frac{P_{2M+1} u_{2M+1} + z}{P_{2M} u_{2M+1} + z}\right) \\
=& \left(\frac{P_M u_M + z}{P_1 u_2 + z}\right)\left(\frac{P_{2M} u_{2M} + z}{P_M u_{M+1} + z}\right)\left(\frac{P_1 u_{2M+1} + z}{P_{2M} u_{2M+1} + z}\right) \\
=& \left(\frac{P_M (k-\mu) + z}{P_1 (k-\mu) + z}\right)\left(\frac{P_{2M}(k+\mu) + z}{P_M (k+\mu) + z}\right)\left(\frac{P_1 k + z}{P_{2M} k + z}\right) \\
=& \left(\frac{k+y}{(1+\mu)k + y}\right)\left(\frac{(1+\mu)^{M-1}(k-\mu) + y}{k-\mu+y}\right)\left(\frac{(1+\mu)(k+\mu) + y}{(1+\mu)^{M-1}(k+\mu) + y}\right),
\end{aligned}
$$

where again $y = z/P_1$, and it is assumed that $k - \mu > 0$.

When $M = 2$, the chained Paasche formula simplifies to:

$$
\begin{aligned}
\prod_{t=1}^{2\cdot 2} CPI^{P}_{t,t+1} =& \left(\frac{k+y}{(1+\mu)k + y}\right)\left(\frac{(1+\mu)(k-\mu) + y}{k-\mu+y}\right) \\
=& 1 - \frac{\mu^2 y}{[k-\mu+y][(1+\mu)k + y]} < 1.
\end{aligned}
$$

We now shown by induction that this inequality also holds for $M \geq 2$. Let us therefore assume for an arbitrary integer number $M \geq 2$ that

$$
\prod_{t=1}^{2M} CPI^{P}_{t,t+1} = \left(\frac{k+y}{(1+\mu)k + y}\right)\left(\frac{(1+\mu)^{M-1}(k-\mu) + y}{k-\mu+y}\right)\left(\frac{(1+\mu)(k+\mu) + y}{(1+\mu)^{M-1}(k+\mu) + y}\right) < 1 \tag{16}
$$

holds. For the inductive step $M \to M+1$, we analyze

$$\begin{aligned}
\prod_{t=1}^{2(M+1)} CPI^P_{t,t+1} &= \left(\frac{k+y}{(1+\mu)k+y}\right)\left(\frac{(1+\mu)^M(k-\mu)+y}{k-\mu+y}\right)\left(\frac{(1+\mu)(k+\mu)+y}{(1+\mu)^M(k+\mu)+y}\right) \\
&= \left(\frac{k+y}{(1+\mu)k+y}\right)\left(\frac{(1+\mu)^{M-1}(k-\mu)+y}{k-\mu+y}\right)\left(\frac{(1+\mu)(k+\mu)+y}{(1+\mu)^{M-1}(k+\mu)+y}\right) \\
&\quad \cdot \left(1-\frac{2\mu^2(1+\mu)^M y}{[(1+\mu)^M(k+\mu)+y][(k-\mu)(1+\mu)^M+y+\mu y]}\right) \\
&\overset{(16)}{<} \left(1-\frac{2\mu^2(1+\mu)^M y}{[(1+\mu)^M(k+\mu)+y][(k-\mu)(1+\mu)^M+y+\mu y]}\right) < 1,
\end{aligned}$$

which concludes the proof.

Conclusion: In the general case, the chained Laspeyres CPI always has a downwards bias. The chained Paasche CPI has an upward bias for $M=1$, and a downward bias for $M \geq 2$.

Case 2: Capital gains are included ex ante with expectations extrapolated over the previous period

In this case the per period user costs are as follows:

$$u_t = \begin{cases} k, & \text{for } t=1, \\ k-\mu < k, & \text{for } 2 \leq t \leq M+1, \\ k+\mu > k, & \text{for } M+2 \leq t \leq 2M+1. \end{cases}$$

Now the chained Laspeyres formula for $M \geq 2$ reduces to the following:

$$\begin{aligned}
\prod_{t=1}^{2M} CPI^L_{m,m+1} &= \left(\frac{P_2u_1+z}{P_1u_1+z}\right)\left(\frac{P_3u_2+z}{P_2u_2+z}\right)\cdots\left(\frac{P_{M+2}u_{M+1}+z}{P_{M+1}u_{M+1}+z}\right) \\
&\quad \cdot \left(\frac{P_{M+3}u_{M+2}+z}{P_{M+2}u_{M+2}+z}\right)\cdots\left(\frac{P_1u_{2M}+z}{P_{2M}u_{2M}+z}\right) \\
&= \left(\frac{P_{2M+1}u_{2M}+z}{P_1u_1+z}\right)\left(\frac{P_2u_1+z}{P_2u_2+z}\right)\left(\frac{P_{M+2}u_{M+1}+z}{P_{M+2}u_{M+2}+z}\right) \\
&= \left(\frac{P_1(k+\mu)+z}{P_1k+z}\right)\left(\frac{P_2k+z}{P_2(k-\mu)+z}\right)\left(\frac{P_{M+2}(k-\mu)+z}{P_{M+2}(k+\mu)+z}\right) \\
&= \left(\frac{k+\mu+y}{k+y}\right)\left(\frac{(1+\mu)k+y}{(1+\mu)(k-\mu)+y}\right)\left(\frac{(1+\mu)^{M-1}(k-\mu)+y}{(1+\mu)^{M-1}(k+\mu)+y}\right),
\end{aligned}$$

where again $y = z/P_1$. When $M = 2$, this reduces to

$$\prod_{t=1}^{2\cdot 2} CPI^L_{t,t+1} = \left(\frac{k+\mu+y}{k+y}\right)\left(\frac{(1+\mu)k+y}{(1+\mu)(k+\mu)+y}\right)$$
$$=1 - \frac{\mu^2 y}{(k+y)[(1+\mu)(k+\mu)+y]} < 1.$$

It can be shown by induction that this inequality also holds for $M \geq 2$. Let us therefore assume that it holds for an arbitrary integer number $M \geq 2$:

$$\prod_{t=1}^{2M} CPI^L_{t,t+1} = \left(\frac{k+\mu+y}{k+y}\right)\left(\frac{(1+\mu)k+y}{(1+\mu)(k-\mu)+y}\right)\left(\frac{(1+\mu)^{M-1}(k-\mu)+y}{(1+\mu)^{M-1}(k+\mu)+y}\right) < 1. \quad (17)$$

For the inductive step $M \to M+1$ we have

$$\prod_{t=1}^{2(M+1)} CPI^L_{t,t+1} = \left(\frac{k+\mu+y}{k+y}\right)\left(\frac{(1+\mu)k+y}{(1+\mu)(k-\mu)+y}\right)\left(\frac{(1+\mu)^{M}(k-\mu)+y}{(1+\mu)^{M}(k+\mu)+y}\right)$$
$$= \left(\frac{k+\mu+y}{k+y}\right)\left(\frac{(1+\mu)k+y}{(1+\mu)(k-\mu)+y}\right)\left(\frac{(1+\mu)^{M-1}(k-\mu)+y}{(1+\mu)^{M-1}(k+\mu)+y}\right)$$
$$\cdot\left(1 - \frac{2\mu^2(1+\mu)^M y}{[(1+\mu)^M(k+\mu)+y][(k-\mu)(1+\mu)^M+y+\mu y]}\right)$$
$$\overset{(17)}{<} 1 - \frac{2\mu^2(1+\mu)^M y}{[(1+\mu)^M(k+\mu)+y][(k-\mu)(1+\mu)^M+y+\mu y]} < 1,$$

which finalises the proof. We again assumed that $k - \mu > 0$.

Hence chained Laspeyres has a downward bias for all integers $M \geq 2$.

For Paasche we have that

$$\prod_{t=1}^{2M} CPI^P_{t,t+1} = \left(\frac{P_2u_2+z}{P_1u_2+z}\right)\left(\frac{P_3u_3+z}{P_2u_3+z}\right)\cdots\left(\frac{P_{M+1}u_{M+1}+z}{P_Mu_{M+1}+z}\right)$$
$$\cdot\left(\frac{P_{M+2}u_{M+2}+z}{P_{M+1}u_{M+2}+z}\right)\cdots\left(\frac{P_1u_{2M+1}+z}{P_{2M}u_{2M+1}+z}\right)$$
$$= \left(\frac{P_{M+1}u_{M+1}+z}{P_1u_2+z}\right)\left(\frac{P_1u_{2M+1}+z}{P_{M+1}u_{M+2}+z}\right)$$
$$= \left(\frac{(1+\mu)^M(k-\mu)+y}{(k-\mu)+y}\right)\left(\frac{(k+\mu)+y}{(1+\mu)^M(k+\mu)+y}\right)$$
$$=1 - \frac{2\mu y[(1+\mu)^M-1]}{[(k-\mu)+y][(1+\mu)^M(k+\mu)+y]} < 1,$$

where again $y = z/P_1$.

Hence chained Paasche has a downward bias for all M.

Conclusion: In the general case, when expected ex ante capital gains are included, a chained Paasche price index always has a downward bias, while a chained Laspeyres price index has an upward bias for $M = 1$, and a downward bias for $M \geq 2$.

A.5 Concluding thoughts on a CPI that includes OOH using a user cost approach

The main findings that emerge from the analysis above are as follows:

(i) Cycles in house prices do not cause bias in a chained Laspeyres or Paasche price index when capital gains are excluded form the user cost.

(ii) Three period case: When capital gains are included ex post, chained Paasche has an upward bias, and chained Laspeyres has a downward bias. When capital gains are included ex ante, the direction of these bias is reversed.

(iii) Five or more periods: When capital gains are included ex post or ex ante, both chained Laspeyres and chained Paasche price indexes are downward biased.

It should be noted that for the ex ante case, we assume that expectations are extrapolated over only one period. Also, in the general multi-period case it is assumed that during the rising (falling) price phase, prices rise (fall) by the same proportion each period.
Some numerical examples for the case of 9 periods (i.e., $M = 5$) are attached. These examples also consider ex ante cases where expected capital gains are extrapolated over more than one period. The general result that emerges here is that the magnitude of the bias falls as the extrapolation time horizon rises.

B Imputing prices and rents using quantile regression

Step 1: Estimating quantile regression models. In the first step hedonic models are estimated. For each year from 2004 to 2014, there are two types of quantile regression models:

one based on rental observations and one based on sold properties. All models have the following structure:

$$Q_{\vartheta}(\log p|X) = \beta_0 + \beta_1 \log(area) + \sum_{j=2}^{4} \beta_j^{bed} \mathbb{1}_{\{j\}}(bed) + \sum_{j=2}^{4} \beta_j^{bath} \mathbb{1}_{\{j\}}(bath) + f(long, lat), \quad (18)$$

where p denotes either the transaction price or the observed rent, X a matrix containing all covariates as well as an intercept, and $\vartheta \in (0, 1)$ a specific quantile level. Due to a lack of sufficient observations with five or six bed- or bathrooms, the four, five and six rooms are merged to a single category. The function $f(long, lat)$ denotes a smoothly estimated geographical spline measuring locational effects on a grid spanned by longitudes and latitudes.[23]

Models are ultimately estimated for nine different quantile levels $\vartheta \in \{0.1, 0.2, \ldots, 0.9\}$. Hence, there are 11 (years) $\times$ 9 (quantile levels) $\times$ 2 (type: sale / rent) $\times$ 2 (type: house / unit) $=$ 396 models. In the following, we refer to a model for rental (R) - or sales (S) - observations in year t and quantile level ϑ by $mod(R, t, \vartheta)$ or $mod(S, t, \vartheta)$.

Step 2: Allocating dwellings to segments. This step ensures that there is a unique price (rent) for each observation per year. Each observation is allocated to a unique price segment indicating its position in the price or rent distribution.

For instance, let $z_{t,h}^R$ denote a dwelling rented in year t, $p_{t,h}^R$ its observed rent, and $x_{t,h}^R$ its set of characteristics. To assign it to an appropriate segment, we impute rents based on its characteristics $x_{t,h}^R$ using models for period t and *all* quantile levels yielding nine different

[23]Locational splines have been used previously by Hill and Scholz (2017) for hedonic imputation house price indexes. Waltl (2017a) adapted this approach to quantile indexes. We follow this method and apply penalized quantile regression models in combination with the triogram method developed by Hansen et al. (1998) and Koenker and Mizera (2004). The smoothing parameter is chosen using an adapted Schwartz Information Criterion as suggested by Koenker et al. (1994).

prices:

$$\begin{aligned}
mod(R,t,0.1) &\longrightarrow \hat{p}^R_{t,h}(\vartheta = 0.1),\\
mod(R,t,0.2) &\longrightarrow \hat{p}^R_{t,h}(\vartheta = 0.2),\\
&\vdots\\
mod(R,t,0.9) &\longrightarrow \hat{p}^R_{t,h}(\vartheta = 0.9).
\end{aligned}$$

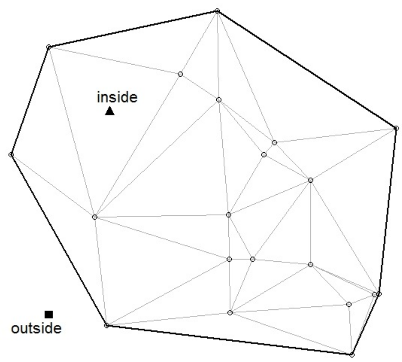
Imputed rents are then compared to the observed rent. The model generating an imputed rent closest to the observed rent is the most appropriate for a particular observation. Observation $z^r_{t,h}$ is assigned to price segment ϑ^* given by

$$\vartheta^* = \arg\min_{\vartheta} \left|\hat{p}^R_{t,h}(\vartheta) - p^R_{t,h}\right|.$$

The segment is then treated like an additional characteristic of each observation indicated by $z^R_{t,h}(\vartheta^*)$ (see Davino et al., 2013, section 4.2.2).

Step 3: Imputing prices and rents. In the third step, prices and rents are imputed for each observation appearing at least once in the data set. Prices and rents are imputed for these observations in every time period.[24] For instance, for observation $z^R_{t,h}(\vartheta^*)$, which was

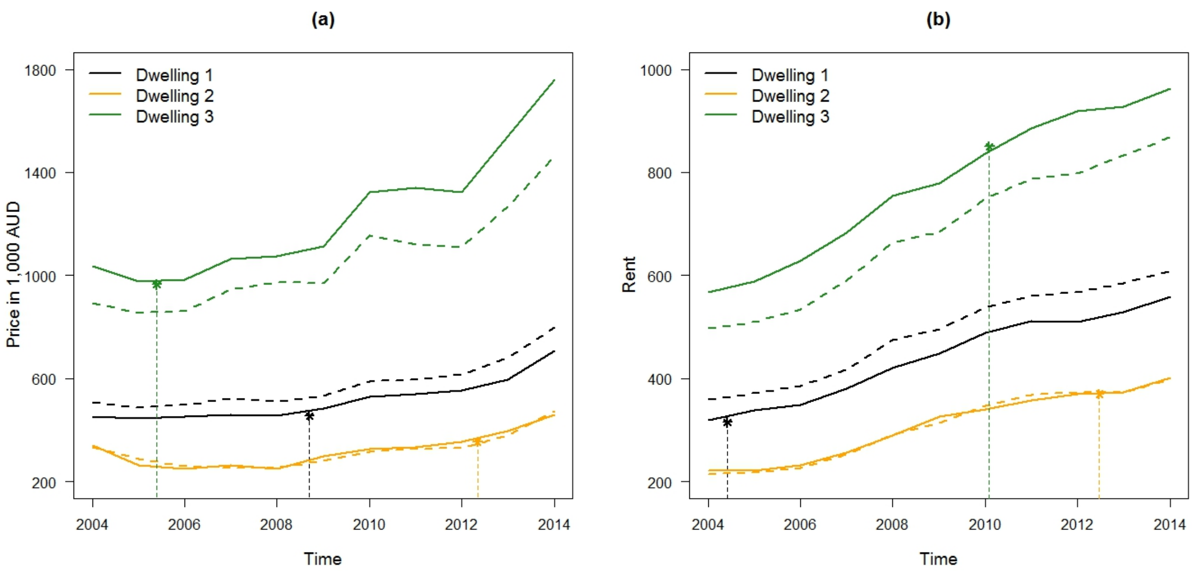
[24] Imputing prices or rents requires a locational spline $f_t(long, lat)$ specific to a particular period to be evaluated. Its support is the convex hull of all locational coordinates of dwellings appearing in period t. Locational effects are obtained for each triangle created from the coordinates using a Delaunay triangulation (see Hansen et al., 1998, and Koenker and Mizera, 2004). It is therefore not possible to directly impute a locational effect for coordinates falling outside the convex hull (see illustration on the right). One could include additional dummy vertices into the Delauny triangulation to increase the support, however this would lead to unfavorable extrapolation which is why we exclude observations that fall outside the intersection of *all* convex hulls (Table C1 reports the number of exclusions).



originally observed in period t, a rent and a price for period s is obtained by evaluating models $mod(R, s, \vartheta^*)$ and $mod(S, s, \vartheta^*)$ for the set of characteristics $x^R_{t,h}$.

Implicitly we assume that segments are comparable between rented and sold houses in the sense that a house that belongs to a top segment in the sales distribution would also belong to a top segment in the rents distribution and vice versa. As we rely on nine quantile levels only, this is not a very restrictive assumption.

Figure B1: Examples of imputed prices and rents.



Notes: The figure plots the temporal development of imputed prices, panel (a), and imputed weekly rents, panel (b), for three houses that were sold and rented some time within the period of observation. The solid lines depict imputed values from conditional quantile models, the dashed lines imputed values from conditional mean models and the stars indicate observed prices and rents. Dwelling 1 is located in the suburban region *Penrith-Windsor*, has four bedrooms and two bathrooms, a land area of $550m^2$ and was assigned to segment 2. Dwelling 2 is located in the metropolitan region *Fairfield-Liverpool*, has three bedrooms and one bathroom, a land area of $612m^2$ and was assigned to segment 5. Dwelling 3 is located in the inner-city region *Inner West*, has three bedrooms and two bathrooms, a land area of $491m^2$ and was assigned to segment 8. Sales prices are measured in 1,000 Australian dollar (AUD) units.

The main advantage of using quantile regression models to impute prices and rents is that observed prices are more reliably replicated than in linear models. With linear models (or generalized linear models), evaluating the model for a specific set of characteristics x would yield an estimate of the *conditional mean* price, $\widehat{\mathbb{E}(\log p|x)}$. Imputed prices and rents are much more strongly clustered around the mean than they would be in reality. Quantile regression, by estimating conditional quantile prices $\widehat{Q_\vartheta(\log p|x)}$, reconstructs observed price and rent distributions much more realistically. Figure B1 illustrates this point by depicting imputed prices and rents together with their observed counterparts for three selected dwellings. Observed prices match very well with imputations from conditional quantile models whereas imputations from conditional mean models do not perform as well.[25] Dwelling 1 in Figure B1 was assigned to segment 2, i.e., a low price segment and the conditional mean model overestimates its price and rent. Dwelling 2 is assigned to segment 5, the median segment, and in this case the conditional mean model predicts its price and rent well. Dwelling 3 is assigned to segment 8, a high price segment. With a conditional mean model its price and rent are underestimated.

With the quantile model, average absolute deviations over all observations are very small (numbers refer to houses/units):

$$\frac{1}{n_R}\sum_{h=1}^{n_R}\left|\frac{\hat{p}_h^R - p_h^R}{p_h^R}\right| = 3.7\% \ / \ 2.9\% \quad \text{and} \quad \frac{1}{n_S}\sum_{h=1}^{n_S}\left|\frac{\hat{p}_h^S - p_h^S}{p_h^S}\right| = 3.4\% \ / \ 4.0\%,$$

where n_R and n_S denotes the number of rental and sales observations. The success of reconstructing observed prices is remarkable. When using a conditional mean model instead of conditional quantile models, average absolute prediction errors are much larger:

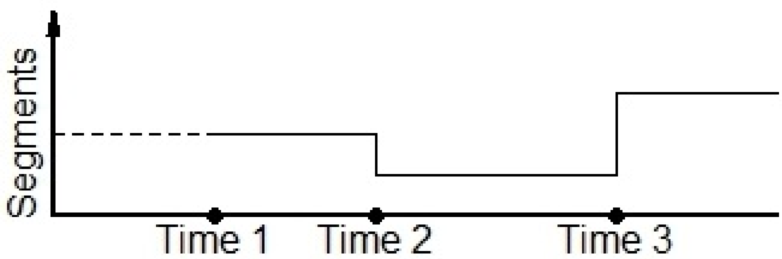
$$\frac{1}{n_R}\sum_{h=1}^{n_R}\left|\frac{\tilde{p}_h^R - p_h^R}{p_h^R}\right| = 13.6\% \ / \ 13.2\% \quad \text{and} \quad \frac{1}{n_S}\sum_{h=1}^{n_S}\left|\frac{\tilde{p}_h^S - p_h^S}{p_h^S}\right| = 13.8\% \ / \ 15.8\%.$$

Step 4: Adjusting imputations for dwellings appearing multiple times in the data set. In this step, adjustments are made for repeated observations. There are many dwellings that appear more than once in the data set either as rental or sales observations. We find that 55.8% (40.2%) of all houses (units) are observed once, 23.2% (24.5%) appear twice and 21.0% (35.3%) at least three times. It happens regularly that a property is assigned to different price

[25] Penalized least squares is used to estimate conditional mean models with specification (18) separately for each year. The locational spline is based on *thin plate regression splines* (see Hill and Scholz 2017). The predicted prices and rents from these models are denoted by $\tilde{p}_h^S$ and $\tilde{p}_h^R$, respectively.

segments over time. Reasons for changes include renovation, depreciation of the structure or changes in locational amenities.[26] Figure B2 illustrates a possible path: The dwelling appears first in the data set at time 1 and is then assigned to a medium segment. The structure depreciates over time such that it is assigned to a low price segment when it re-appears at time 2. The dwelling undergoes renovation and appears on the market again at time 3 and is then assigned to a high price segment. To obtain unique imputed prices and rents per year, we allow changes in the allocation to segments and use the respective imputed prices and rents. For the illustrated path in Figure B2 this implies that the dwelling is assigned to the medium segment in the time interval [2004; time 2), to the low segment in [time 2; time 3) and to the high segment in [time 3; 2014].

Figure B2: Illustration of temporal changes in the segment allocation.



Step 5: Identification of owner occupied and rented dwellings. Generally, we assume that dwellings that are sold are owner occupied and those that are rented are not. The allocation of a specific dwelling may – as with step 4 – change over time. If a dwelling was sold at time 1, rented at time 2 and again sold at time 3, we allocate the dwelling to the OOH sample in [2004, time 2) and [time 3, 2014]. In the interval [time 2, time 3) it is assigned to the rental sample.

[26]Of course, measurement errors as well as errors resulting from differences between segments according to the price and rent distribution may also lead to changes in the segment allocation.

C Additional Tables

Table C1: Summary Statistics

HOUSES			UNITS		
Weekly rents in AUD and **sales prices** in thousand AUD					
Median	470	650	Median	410	444
Mean	569	826	Mean	450	520
[Q1; Q3]	[360; 650]	[450; 950]	[Q1; Q3]	[330;525]	[336; 590]
Land area in m^2					
Median	573	590	Median	1,191	1,397
Mean	657	636	Mean	1,783	2,024
[Q1; Q3]	[404; 715]	[465; 721]	[Q1; Q3]	[697; 2 155]	[804; 2 543]
Number of bedrooms in %					
1	2.35	0.31	1	28.50	20.27
2	16.23	8.75	2	60.33	63.39
3	51.57	45.62	3	10.43	14.78
4+	29.85	45.32	4+	0.74	1.56
Number of bathrooms in %					
1	60.30	44.27	1	77.17	66.72
2	31.31	39.53	2	21.94	31.71
3	7.23	13.61	3	0.85	1.48
4+	1.16	2.59	4+	0.05	0.10
Number of observations					
All	330 102	427 211		521 518	343 437
− incomplete	20 884	105 053		49 623	165 077
+ reconstructed	2 456	19 044		8 688	37 788
− convex hull	569	840		5	0
Final	311 105	340 362		480 578	216 148
in % of all	94.3%	79.7%		92.2%	62.9%

Notes: Numbers refer to rental (left columns) and sales data (right columns). *All* refers to all observations (after deletions as described above) and *final* to the final number of observations. Observations that are not located in the intersection of locational convex hulls are excluded (see footnote 24).

Table C2: Average Monthly OOH Expenditures in Dollars: Sydney 2004-2014

	$u(0)$	$u(10)$	$u(20)$	$u(30)$	Rental Equiv.	Acquis.
2004	2 140.9	0.0	450.6	1 024.2	1 016.9	606.2
2005	1 857.4	0.0	289.9	754.2	1 046.6	629.4
2006	2 077.0	229.0	625.3	984.8	1 094.7	637.8
2007	2 364.4	484.8	781.0	1 147.8	1 194.4	646.2
2008	2 494.1	801.3	1 033.6	1 248.2	1 339.4	672.6
2009	2 207.9	975.8	1 537.1	1 110.6	1 354.7	689.9
2010	2 348.2	764.6	1 091.0	1 167.5	1 462.1	711.2
2011	2 273.2	666.7	959.9	1 220.9	1 549.4	732.7
2012	1 411.0	534.9	199.8	304.8	1 585.8	744.9
2013	1 802.2	1485.4	441.6	410.4	1 625.6	770.8
2014	2 165.2	1820.0	315.6	341.3	1 676.8	802.3
Average	2 103.8	705.7	702.3	883.2	1 358.8	694.9
CV	0.147	0.806	0.594	0.416	0.178	0.091

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SOCIO-ECONOMIC RESEARCH

11, Porte des Sciences
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L-4366 Esch-sur-Alzette

T +352 58 58 55-1
F +352 58 58 55-700

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