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Time to build and the real-options channel of residential investment[☆]

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ABSTRACT

A standard real-options model predicts that time-to-build investment could be delayed by uncertainty over future revenue. We quantify the first-order importance of this mechanism in the 2002–2011 housing boom-bust cycle by developing and estimating a model of sequential irreversible investment with stochastic bottlenecks. We find that the main driver of construction delays during the boom is construction bottlenecks. However, further delay in construction during the bust is caused by an increase in uncertainty, which grew by 21.6% between 2002 and 2009. The model can account for more than one-third of the decline in residential investment between 2002 and 2009.

1. Introduction

Many investment projects are irreversible, their future payoffs are uncertain, and the timing of investment is flexible. The real-options theory of investment considers optimal investment decisions under such conditions, as articulated in Dixit and Pindyck (1994). The models predict that the option value of waiting for new information influences the optimal investment decision.

This paper investigates residential investment in the 2002–2011 housing boom-bust cycle through the lens of the real-options mechanism. A key observation that motivates our paper is shown in Fig. 1. The average times from start to completion for both single-family and multi-family houses were stable between 1984 and 2002, but those times shifted upward by two and four months between 2002 and 2009, respectively. This translates into a 25% to 40% slowdown in average construction intensity per house under construction. This study quantitatively assesses the role of uncertainty in accounting for the sizable delay in construction during the housing cycle. To this end, we develop and estimate a sequential irreversible investment model with stochastic bottlenecks based on Majd and Pindyck (1987). The key predictions of the model are that low price level, high price uncertainty, and high bottleneck probability all delay the completion of a project.

Using micro-data on residential construction, we estimate our model based on simulated method of moments (SMM). Our parameter estimates allow us to quantify the

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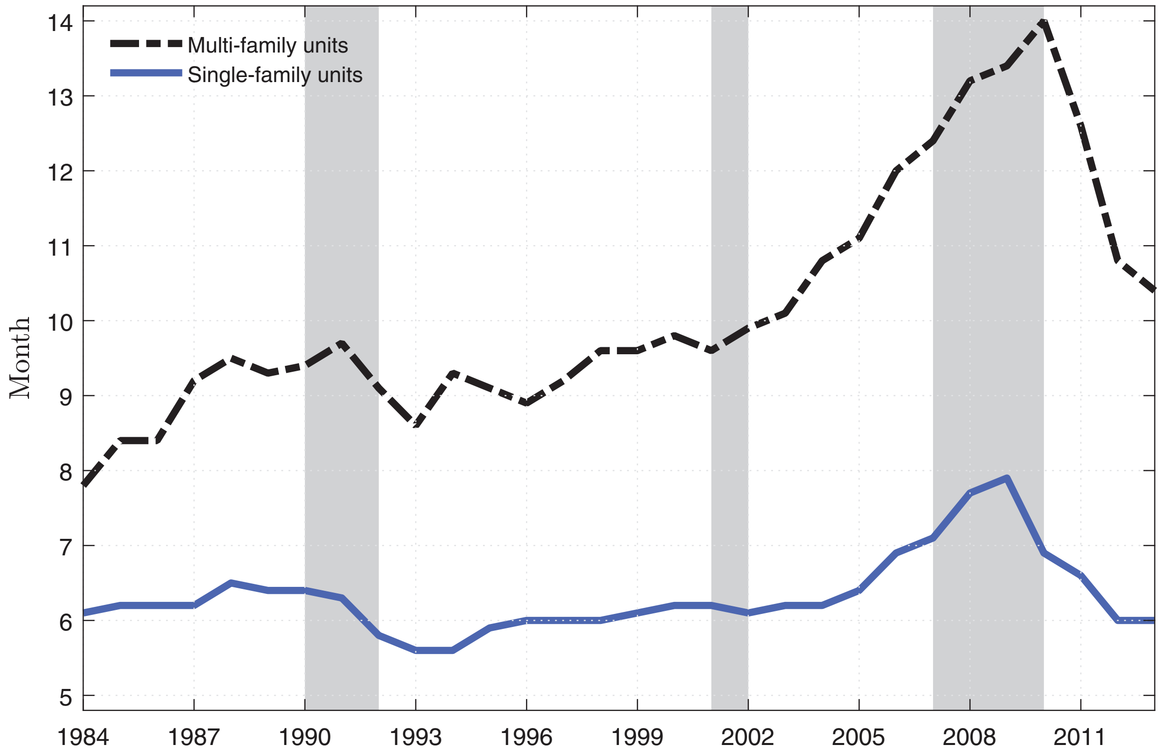

Fig. 1. Time to build for completed houses in the US. Shaded areas are recessions dated by the National Bureau of Economic Research.

roles of bottlenecks, price levels, and uncertainty in accounting for the increase in time to build (TTB) during the housing cycle. The estimation results display a striking difference in the interpretation of construction delays during the boom and bust. The main driver of construction delays in 2006 is construction bottlenecks, which increased by 23.7% between 2002 and 2006. On the other hand, the dominant factor behind the further increase in TTB in 2009 is an increase in uncertainty, which grew by 21.6% in standard deviation between 2002 and 2009. Construction bottlenecks were less frequent in 2009 than in 2002.

A novelty of this study is that we look into an investment margin that has not been discussed in the recent housing cycle: the TTB of residential investment. Most studies on residential investment have focused on its extensive margin: new housing starts. We argue that movements in TTB have also been crucial in shaping housing dynamics, for two reasons.[1]

First, the stock of incomplete houses is large. Building a house takes time. Even after building permits are issued, the average single-family house takes six months from start (i.e., excavation) to finish. Multi-family houses take around ten months to build. As a result, for each housing unit started in a given month, an average of 8.3 housing units are under construction, as shown by data from December 1969 to December 2014. With such a large stock of incomplete houses relative to new housing starts, even small variations in the construction intensity of incomplete houses can significantly affect the movement of residential investment. TTB has a sharp inverse relation with the average construction intensity of a house.

Second, TTB affects housing start decisions. Forward-looking homebuilders will consider their expected investment intensity during the entire construction process.[2] Therefore, any shift in TTB should also affect new housing starts and thus residential investment.

To verify the quantitative importance of TTB dynamics in shaping housing starts and residential investment, we conduct a counterfactual exercise with a version of our model in which the endogenous TTB channel is completely shut down. Our real-options TTB model predicts a deeper investment slump in 2009 (more than twice as deep) than that predicted by the fixed TTB model. The real-options TTB model can account for over one-third of the decline in residential investment between 2002 and 2009.

[1] New construction is by far the largest component of residential investment in gross domestic product. Residential investment also includes improvements to existing houses, brokers' commissions, and other ownership transfer costs, which are not the focus of this paper.

[2] These forward-looking aspects, such as gestation lags or flow adjustment costs, have been widely used in the business cycle literature to explain various dynamic responses observed in the data. For example, Christiano, Eichenbaum and Evans (2005) introduce investment adjustment costs to generate hump-shaped investment responses to monetary shocks, and Uribe (1997) introduces gestation lags and convex adjustment costs to capital accumulation to generate the observed slow convergence of inflation between non-tradables and tradables in an experiment with an exchange rate–based stabilization plan. More recently, Arezki, Ramey and Sheng (2017) use gestation lags for an application of the effects of news shocks in an open economy.

Related literature. Although the significant cyclicality and volatility of the housing market were well known before the Great Recession (Davis and Heathcote, 2005), the most recent housing boom-bust cycle was unprecedented in size. House prices were also volatile, and measures of uncertainty were high during the bust period. For example, Jurado, Ludvigson and Ng (2015) and Shin and Zhong (2019) estimated high uncertainty during the Great Recession. These facts motivate us to examine the real-options implications of residential investment dynamics in the recent housing market.

The real-options channel of investment has been a major topic of interest in both macroeconomics and financial economics. The theoretical channels are well summarized in Dixit and Pindyck (1994), and their empirical applications are widespread across both fields, such as in Leahy and Whited (1996), Moel and Tufano (2002), Bloom, Bond and Van Reenen (2007), Bulan, Mayer and Somerville (2009), Bloom (2009), Bachmann, Elstner and Sims (2013), and Gilchrist, Sim and Zakrajšek (2014).

However, extensions of real-options insights to TTB investment decisions have been less fully explored. Following Kydland and Prescott (1982), TTB investment is typically assumed to be exogenous from business cycles (Campbell, 1998; Lucca, 2007; Edge, 2007).[3] Although this assumption seems innocuous most of the time, TTB shifted significantly during the Great Recession.

We are the first to show this shift using micro-data on residential TTB across the US. We also develop a structural model of both endogenous and exogenous TTB investment based on Majd and Pindyck (1987) and discipline the model using empirical moments constructed from the micro-data. Our estimation contributes to the real-options literature by quantifying the uncertainty effects on TTB investment in the recent housing cycle.[4] Moreover, the estimated time-varying bottleneck friction is often discussed in the literature but has not been analyzed through a structural model.

From a broader perspective, by documenting new findings on residential construction and exploring their housing supply implications, this paper contributes to the housing investment literature, following Topel and Rosen (1988), Iacoviello (2005), Glaeser, Gyourko and Saks (2005), Leamer (2007), Glaeser, Gyourko and Saiz (2008), Saiz (2010), Haughwout, Peach, Sporn and Tracy (2013), and Kydland, Rupert and Sustek (2016).

The rest of the paper is organized as follows. Section 2 develops the model. Section 3 analyzes the micro-data on residential construction. Section 4 describes the simulation and estimation methodologies and presents the estimation results. Section 5 presents a counterfactual exercise, and Section 6 concludes the paper. The Online Appendix contains additional micro-data analyses and provides details on the model estimation method and additional estimation results.

[3] Recently, Meier (2018) finds that TTB for capital goods is countercyclical and is responsive to supply chain disruptions.

[4] That extensive and intensive investment deserve separate attention is also posited by Jovanovic and Rousseau (2014), who argue that cyclical investment behavior differs between established and new firms.

Table 1
Single-family house construction cost breakdown, 2013. Survey data are from the National Association of Home Builders.

Stage of construction	Cumulative (%)
(1) Site work (permits, inspections, architecture)	6.8
(2) Foundation (excavation, concrete)	16.3
(3) Framing (roof, metal, steel)	35.4
(4) Exterior finishes (wall, windows, doors)	49.8
(5) Major systems rough-in (plumbing, electrical, HVAC)	63.2
(6) Interior finishing (insulation, painting, lighting, flooring)	92.5
(7) Final steps (landscaping, outdoor structures, clean up)	99.1
(8) Other	100.0

2. Model of time to build

Housing supply decisions generally involve significant irreversible costs, such as resources spent on acquiring permits and building foundations and the time spent on construction. The irreversible resources and time required by these investments introduce a significant option value not only at the beginning of construction but also at the continuation stage. As shown in Table 1, homebuilders report a large amount of spending in the later stages of construction. Only 16.3% of the total construction cost has been spent when the foundation is completed. Thus, continuing the project from that stage requires significant resources and time.

Motivated by these facts, we develop a real-options model of TTB investment with stochastic bottlenecks. The goal of this section is to understand the theoretical channels of irreversible TTB investment decisions in the face of uncertainty and occasional bottlenecks. In later sections, the model is estimated using our micro-data moments to quantify its channels in the recent housing boom and bust.

2.1. Model description

We develop a model in which a project takes time to complete and involves multiple irreversible stages and occasional bottlenecks. Payoff occurs only after the project is finished. Irreversible investment decisions are made sequentially at each stage amid uncertainty about the future payoff. Investment delays occur either endogenously due to uncertainty or exogenously due to bottlenecks.

The model blends three key elements that are widely discussed in the investment literature. First, a real-options channel is introduced by illustrating a discrete-time version of the sequential irreversible investment model of Majd and Pindyck (1987) and Dixit and Pindyck (1994). Second, we study the effect of uncertainty on investment following Bloom (2009). Third, the model incorporates stochastic bottleneck probabilities that delay TTB investment independent of the real-options mechanism. These bottlenecks could be interpreted as either input (labor and material) bottlenecks or weather effects that an individual builder could consider exogenous.

2.1.1. TTB and investment

A house requires a total real investment of $\bar{K}$. In each period, the maximum level of investment is κ. If $\kappa \geq \bar{K}$, then the project can be completed in one period. If $\kappa < \bar{K}$, then the investment takes time to build, with physical TTB being $\bar{K}/\kappa$.

A bottleneck probability for ongoing projects also exists. In each period, bottlenecks occur with a probability of p_c. Investment is delayed when bottlenecks occur, and the expected minimum TTB with bottlenecks is

$$1 + \frac{\bar{K}/\kappa - 1}{1 - p_c}. \quad (1)$$

Without bottlenecks ($p_c = 0$), the expected minimum TTB is equal to the physical TTB.

2.1.2. Price dynamics

The value of a completed house i in period t is denoted as P_{it}. This value is determined by both a macro price factor P^M and a construction unit idiosyncratic factor P_{it}^U:

$$P_{it} = P^M \times P_{it}^U. \quad (2)$$

The stochastic process for P_{it}^U is

$$log(P_{it}^U) = log(P_{it-1}^U) - \frac{\sigma^2}{2} + \sigma W_{it}, \quad W_{it} \sim N(0, 1), \quad (3)$$

where σ is the level of uncertainty in this price process and W_{it} is the idiosyncratic price innovation term. In this process, the mean growth rate of the idiosyncratic price factor is zero regardless of the level of uncertainty. For construction that has not started, we normalize the previous value to one ($P_{it-1}^U = 1$).

In the price process, P^M and σ are assumed to be constant. Therefore, builders in this model face house price movements driven by time-varying idiosyncratic price factors rather than by macro price or uncertainty factors. Although this assumption could be reasonable in the short term, macro-level movements are also relevant in the medium term, especially during the most recent boom-bust cycle. Later in the simulation, we allow the macro price and uncertainty factors to be time-varying across regimes and study their roles in the housing boom and bust.

2.1.3. State evolution

In addition to the price factor, the two other state variables for builders are B_{it} and K_{it}. The variable B_{it} is an indicator function for a construction bottleneck for house i in period t. Bottlenecks occur with probability p_c, which gives

$$B_{it} = \begin{cases} 1 & \text{with probability} \quad p_c \\ 0 & \text{with probability} \quad 1 - p_c. \end{cases} \quad (4)$$

The variable K_{it} is the total remaining capital for the completion of house i in period t. Denoting I_{it} as the flow cost of investment, K_{it+1} evolves into

$$K_{it+1} = K_{it} - (1 - B_{it})I_{it}. \quad (5)$$

Thus, without bottlenecks ($B_{it} = 0$), current investment reduces the future remaining capital of the house under construction. When a bottleneck occurs ($B_{it} = 1$), no construction progress takes place ($K_{it+1} = K_{it}$). A house is completed when $K_{it} = 0$, and a house is yet to be started when $K_{it} = \bar{K}$.

To introduce the notion of depreciation during the construction process, we also assume that the builder incurs a maintenance cost until the house is completed. In each period, the builder pays a maintenance cost m for each incomplete capital $\bar{K} - K_{it}$. Due to maintenance, existing capital does not depreciate.

2.1.4. Bellman equation

The builder's value $V(\cdot)$ of an incomplete house i with a current construction unit price factor P_{it}^U, $K_{it} > 0$ remaining capital to completion, and bottleneck indicator B_{it} is

$$\begin{aligned} &V(P_{it}^U, K_{it}, B_{it}; \Lambda) \\ &= \max_{I_{it} \in \{0,\kappa\}} \Big\{ -(1 - B_{it})I_{it} - m(\bar{K} - K_{it}) - \gamma 1_{\{K_{it}=\bar{K} \ \& \ I_{it}>0\}} \\ &\quad + \left(\frac{1}{1+r}\right)\mathbb{E}V(P_{it+1}^U, K_{it+1}, B_{it+1}; \Lambda)\Big\}, \end{aligned} \quad (6)$$

where $\Lambda = \{p_c, P^M, \sigma\}$ and variable $1_{\{x\}}$ is an indicator function of x being true. Without bottlenecks ($B_{it} = 0$), the cost of real investment in each stage is I_{it}. When starting to build a new house ($K_{it} = \bar{K}$), the builder pays an additional fixed cost γ to start construction ($I_{it} > 0$). This cost parameter incorporates the various sunk costs invested in the decision to start a house, such as obtaining building permits. Builders with an incomplete house pay a maintenance cost m for each existing capital $\bar{K} - K_{it}$. The builder discounts the future consistent with the real interest rate r. TTB investment decisions are discrete (either invest κ or not).[5] The evolution functions of the three individual state variables are Eqs. (3)–(5).

The value of completed house i ($K_{it} = 0$) is

$$V(P_{it}^U, K_{it}, B_{it}; \Lambda) = P^M P_{it}^U. \quad (7)$$

Hence, when a house is finished, the builder earns its market price.

2.2. Model solution

The solution of the model is characterized by a threshold price of investment, above which the builder invests. A builder without an ongoing project decides whether to start a new house, and a builder with an ongoing project decides whether to continue it. Both types of investment decisions depend on the bottleneck and price channels (macro price factor and idiosyncratic price uncertainty).

2.2.1. Current bottleneck and investment

When a current bottleneck occurs ($B_i = 1$), the threshold price is infinity, and the builder does not invest regardless of the observed price. Bottlenecks capture the delays in investment (both new and TTB) that are unrelated to the real-options channel.

[5] In a continuous-time model without adjustment costs, this bang-bang type of TTB investment turns out to be the solution to the model even when a continuous range is considered (Dixit and Pindyck, 1994). In general, this discrete investment decision assumption could be relaxed by solving the model with a higher frequency and aggregating across time.

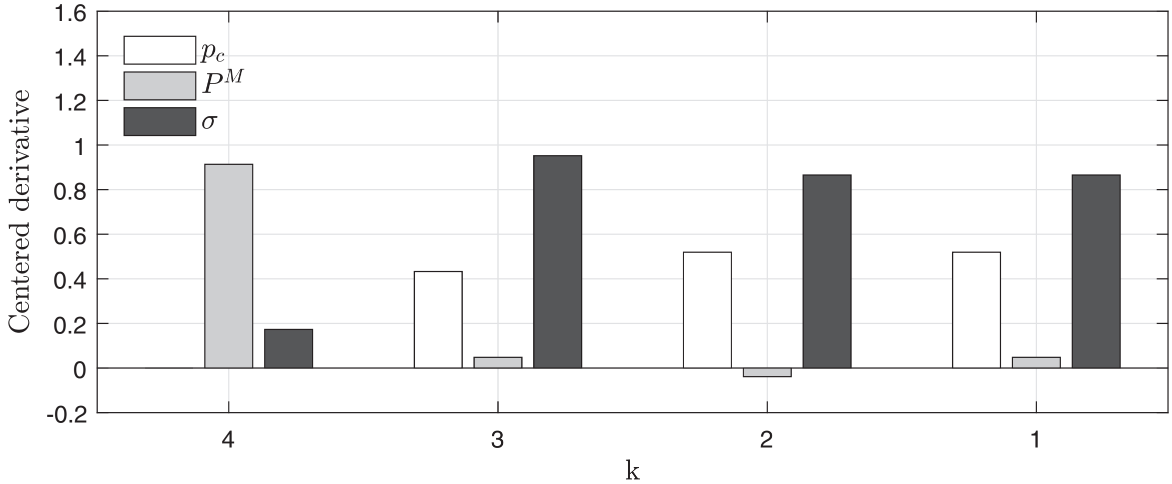

Fig. 2. Comparative statics for the investment price threshold. Displayed values are the log-centered differentiations of the investment price threshold of the model defined in Eq. (9) for each parameter (p_c, P^M, σ), with increment $h = 0.02$.

2.2.2. Investment and price

When no bottleneck occurs ($B_i = 0$), the optimal threshold price, $P^*(K_i;\ \Lambda)$, can be solved for each K_i stage of construction. The builder's investment decision is

$$I_{it} = \begin{cases} \kappa & \text{if } P_{it} \geq P^*(K_i;\ \Lambda), \\ 0 & \text{if } P_{it} < P^*(K_i;\ \Lambda), \end{cases} \tag{8}$$

where $\Lambda = \{p_c, P^M, \sigma\}$. $P^*(\bar{K};\ \Lambda)$ indicates the threshold price for housing start decisions, and $P^*(K_i;\ \Lambda)$ for $K_i < \bar{K}$ refers to the threshold price for TTB investment decisions with remaining construction of K_i. For a housing start decision, the idiosyncratic price is drawn from a log-normal distribution with its mean at the macro price factor P^M. Therefore, the builder is not forced to start construction on a pre-constructed structure or in an area with a history of bad prices. For the TTB investment decision on incomplete construction, the idiosyncratic price is drawn based on its previous price. Thus, once a housing start decision is made and the foundations are laid, the building is locked into its own history of shocks.

2.2.3. Numerical example

The model does not allow an analytical solution (Majd and Pindyck, 1987), so we solve it numerically. The parameter values are discussed in Section 4. We set $p_c = 0.337$, $P^M = 2.098$, and annualized $\sigma = 0.398$ as the benchmark numerical values, which are their respective estimates for 2002. In this section, we provide the qualitative implications of our model based on those parameter values. We assess the sensitivity of investment decisions with regard to three parameters that represent bottleneck (p_c), macro price level (P^M), and price uncertainty (σ) channels.

For each of the three parameters, the log-centered differentiations of the investment price threshold at each investment stage are computed. For example, the log-centered differentiation for the bottleneck parameter at investment stage k with increment h is

$$\frac{\Delta_{\pm h} \log\left(P^*(k;\ \Lambda)\right)}{\Delta_{\pm h} \log p_c} \equiv \frac{\log\left(P^*(k;\ \Lambda_{+h})\right) - \log\left(P^*(k;\ \Lambda_{-h})\right)}{\log\left((1+h)p_c\right) - \log\left((1-h)p_c\right)}, \tag{9}$$

where $\Delta_{\pm h}$ is the centered differentiation operator with increment h, with $\Lambda_{+h} = \{(1+h)p_c, P^M, \sigma\}$ and $\Lambda_{-h} = \{(1-h)p_c, P^M, \sigma\}$. The measures for the macro price level and the price uncertainty are similarly computed. Fig. 2 displays the log-centered differentiation for the three parameters at each investment stage ($k = 4, 3, 2, 1$). We highlight three results from the figure.

First, higher future bottleneck probability has no effect on the start price threshold ($k = 4$) but increases the price thresholds for TTB investment ($k = 3, 2, 1$). With higher bottleneck probabilities, the builder with an existing construction project expects longer construction delays, which discounts its expected profit by the interest rate and also increases its maintenance cost for existing structures. To make up for these additional costs, the builder asks for a higher price threshold to invest. On the other hand, the builder who is deciding to start a new project does not have to deal with the maintenance cost. At the same time, because the idiosyncratic start price draw is independent and identically distributed with the mean set at the macro price, forgoing the opportunity to start with a good price draw is costly. Therefore, a higher future bottleneck probability is neutral to the start decision.

Second, a higher macro price increases the start price threshold but has only slight effects on the price thresholds for TTB investment. The increase in the start price threshold is below one. Because the price threshold is a combination of the macro price and the idiosyncratic price threshold, as in Eq. (2), this implies that builders with a higher macro price are willing to start construction even at a worse draw of the idiosyncratic price. Builders who have already started a house do not change the investment price threshold, because a (permanent) shift in the macro price is perceived to be identical to a change in the idiosyncratic price, given its geometric random walk process. The investment behavior of the builder could change, but the price threshold itself does not respond to price shifts. Therefore, the idiosyncratic price threshold falls to cancel out the increase in the macro price.

Third, higher uncertainty increases both the start and TTB investment price thresholds. This result is consistent with Majd and Pindyck (1987), who find that higher uncertainty increases the option value of both start and TTB investment.

Overall, we find that TTB investment decisions are sensitive to all three parameters of interest. Higher bottleneck probability, lower macro price, and higher uncertainty all deter continuing investments in existing construction, which is reflected in the higher idiosyncratic price thresholds.

2.2.4. Summary

Our model incorporates both a price channel (real options) and a non-price channel (bottlenecks) to explain delays in TTB investment. Our numerical example stresses that the price threshold for TTB investment increases with higher future bottleneck probability, lower macro price level, and higher idiosyncratic price uncertainty. In the model, builders of existing construction projects (intensive investment) are as sensitive to housing market conditions as builders contemplating whether to start a new project (extensive investment).

3. Data

We use Survey of Construction data from the US Census Bureau. This is a national sample survey (sampling rate: 1/50) of the builders and owners of new houses. The data set contains information on the building and geographic characteristics of new houses across the US in each survey year, including the starting and completion months of the houses, sales prices, and the month in which each house was sold (if it was), along with its square footage and number of rooms. Houses authorized by building permits, but that have not been started by the end of the survey year or those that are under construction, are also included. Houses for which construction was abandoned after permit issuance or after the start of construction are not included.

Using this data set, we study the distribution of TTB for single-family houses built for sale during the most recent housing boom and bust from 2002 to 2011.[6] Our goal is to understand the change in the distribution of TTB that drove the two-month increase in average TTB for single-family houses between 2002 and 2009 as observed in Fig. 1. In connection to the real-options channel, we analyze the new house prices and their dispersion during this period.

[6] The micro-data for single-family houses are publicly available dating back to 1999. Built-for-sale houses are 74% of the total sample. The remaining building purpose categories are contractor-built, owner-built, and built-for-rent houses, accounting for 14%, 9%, and 3% of the total sample, respectively.

Table 2
Regression on time to build (TTB in log values). Number of observations in the regression is 111,628.

Control variables	Frequency	Estimate	Standard error
New England	0.019	0.304	0.01601
Middle Atlantic	0.052	0.296	0.01110
East North Central	0.095	0.205	0.00885
West North Central	0.067	0.194	0.10631
South Atlantic	0.306	0.064	0.00689
East South Central	0.054	0.141	0.00925
West South Central	0.142	–	
Mountain	0.119	0.057	0.00895
Pacific	0.146	0.194	0.00885
Modular	0.010	−0.280	0.02293
Panelized	0.023	−0.162	0.01000
Site built	0.967	–	
Square feet (×100)		0.008	0.00028
Constant		1.507	0.01816
Other controls			
Metropolitan area		Yes	
Number of full baths		Yes	
Number of stories		Yes	
Detached		Yes	
Deck		Yes	
Parking facility		Yes	
Foundation		Yes	
Material of wall		Yes	

3.1. Micro-level time to build

We first construct a measure of economic TTB by controlling for the geographic and building characteristics of each completed house and then we compare its cross-sectional distribution over time.

3.1.1. Economic time to build

As every building is different, each TTB depends on various factors. For example, a large, difficult-to-build house will require lengthy construction time. Other factors that cause lengthy construction include weather conditions and building regulations.

We focus on the dynamics of TTB that are independent of such geographic and building characteristics.[7] Because the micro-data provide many of these features, we use them to construct a measure of economic TTB for each completed built-for-sale single-family dwelling in the US. For geographical characteristics, we control for the nine Census Bureau divisions and whether the house is built in a metropolitan area, which is the finest level of geographical information available in the public data. For building characteristics, the list of control variables includes building method (site built, panelized, modular) and the square footage of the house.

We regress the log of TTB on the control variables.[8] Table 2 reports the results of this regression using data

[7] We understand that building and geographic characteristics can be correlated with economic conditions. For example, larger houses can be built during boom periods. Therefore, our estimate should be considered as a conservative measure. Because our focus is on the dynamics of TTB while controlling for housing start decisions, we find it best to ignore these possible correlations.

[8] The qualitative discussions are similar even if we regress on the level of TTB instead of the log. Because a log regression provides estimates in

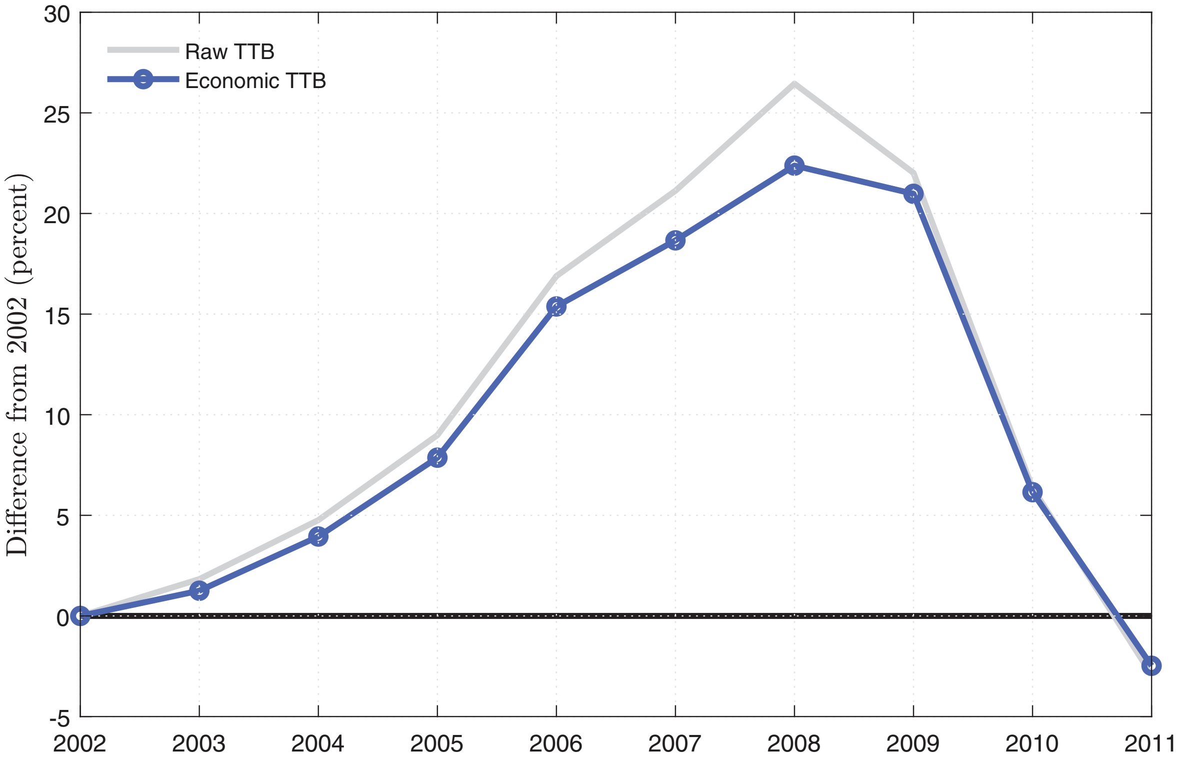

Fig. 3. Mean economic time to build (TTB) for built-for-sale single-family houses. Economic TTB in each year is the mean TTB of a representative house in the overall sample plus the sum of each year's estimated residuals, based on the regression in Table 2.

for all houses completed between 2002 and 2011. Although our main focus is not on understanding the links between the control variables and TTB, several interesting results are worth mentioning. The first column summarizes the frequency of the sample. The South Atlantic is the division with the highest number of completed houses during the sample period, accounting for 30.6% of the total sample. The fewest houses were built in New England (1.9%).

Analyzing the regression, we notice first that the New England, Middle Atlantic, and East North Central divisions show longer TTB than the other divisions do. TTB is on average 30.4% higher in New England than it is in the West South Central division. Second, site-built houses have longer TTB than panelized or modular houses have, which could reflect exposure to poor weather conditions. Third, the square footage of a house has a positive correlation with TTB.

In our subsequent analyses, we use the residual of the regression in Table 2 as our measure of economic TTB.

3.1.2. Average economic time to build

Based on the measure of economic TTB, we construct an annual time series of the average economic TTB for the representative built-for-sale house in our sample. The representative house is a dwelling with average observable characteristics relative to the total sample. In Fig. 3, we compare its pattern with the average TTB in the raw data.

We find that average TTB has increased significantly for both the raw data and the economic TTB measure. This implies that the increase in raw average TTB is not mainly a result of composition effects. The increase in TTB during the housing boom and bust period is only mildly explained by larger, higher-quality houses being built during this period.

We also find that average economic TTB increased by 23% between 2002 and 2008. The average economic TTB increased by 15% by 2006. It then continued to increase between 2006 and 2008 and remained high in 2009.[9]

3.1.3. Distribution of economic time to build

In this section, we discuss the dynamics of the underlying distribution of economic TTB that leads to the increase in the average value. We compare the cross-sectional distribution of TTB across three periods: steady state (2002–2003), housing boom (2004–2006), and the subsequent bust (2007–2009). Fig. 4 plots the distribution of economic TTB for 2002, 2005, and 2009.

Panel A of Fig. 4 compares the kernel density of economic TTB in 2002 and 2005. Between those years, this

percentage terms, we use it as a baseline. The level TTB regression is provided in the Online Appendix.

[9] Whereas the average raw TTB of built-for-sale single-family houses peaked in 2008, that of all single-family houses peaked in 2009 due to delays in the construction of owner-built and contractor-built houses (see Fig. 1).

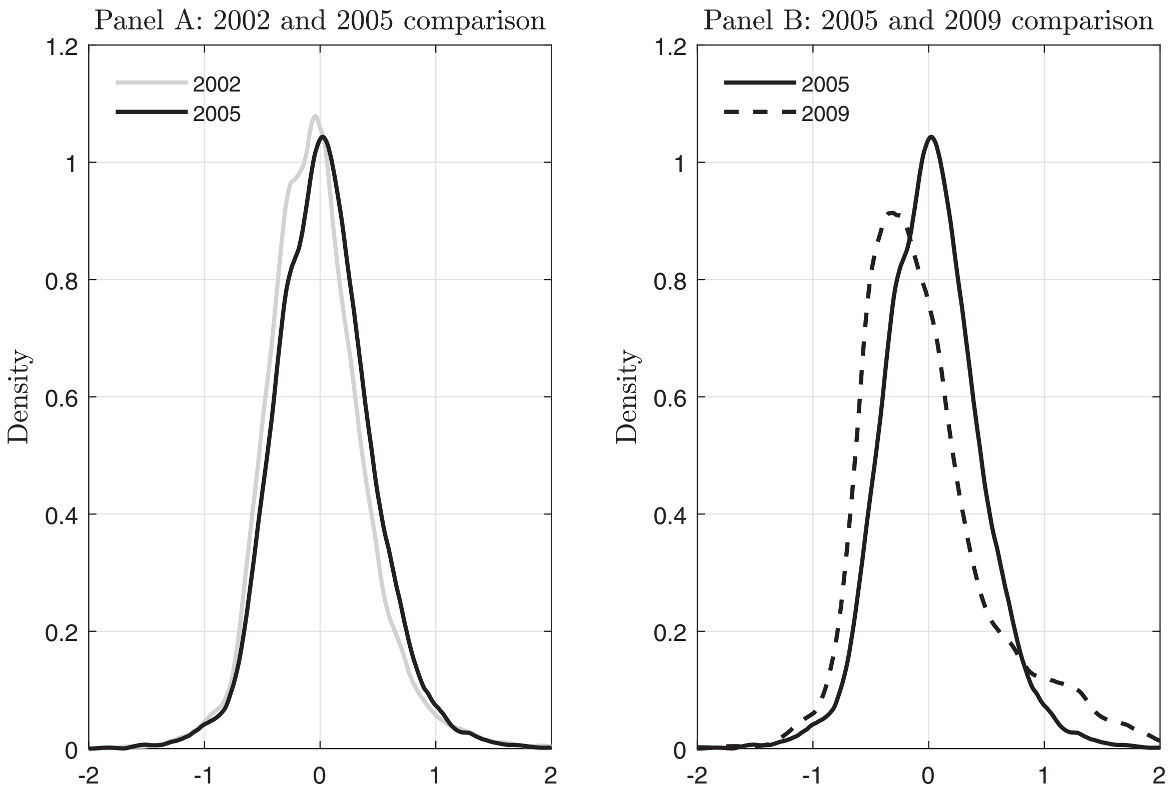

Fig. 4. Distribution of economic time to build (TTB). The kernel density of economic TTB for all single-family houses in log values. The value 0 in the x-axis refers to the ten-year average economic TTB. Panel A compares 2002 and 2005, and Panel B compares 2005 and 2009.

distribution exhibited an overall shift to the right. Thus, economic TTB increased for all types of houses.

Panel B of Fig. 4 compares the kernel density of economic TTB in 2005 and 2009. Two patterns are apparent. First, the mass of the distribution (including the mode) shifted back to the left. Second, a fat tail appeared at the right. In the Online Appendix, we compute the sample skewness for each year and find that the measure in 2009 is statistically greater than that in 2005. Whereas most houses took less time to complete in 2009, a few houses showed lengthy TTB. The long delay in the construction of those houses contributed to the further increase in average TTB between 2005 and 2009, as illustrated in Fig. 3.

3.2. Bottlenecks and time to build

The increase in TTB could be linked to bottleneck effects such as a shortage of construction inputs. In Fig. 5, we plot several construction sector time series. We observe that construction activity, such as housing starts and construction employment, surged in the boom period. We also plot two measures of bottlenecks in the construction sector based on data from the Bureau of Labor Statistics (BLS): (1) construction sector unemployment rate and (2) construction sector labor market tightness, which is the ratio of job openings to unemployment. The low unemployment rate and high labor market tightness support the view that a timely hiring of workers in the construction sector during the housing boom period was a challenge (Green, Malpezzi and Mayo, 2005).

In the housing bust between 2007 and 2009, the measures in the construction sector no longer support the view that bottlenecks were the main contributor to the further increase in TTB. As shown in Fig. 5, a dramatic decrease is evident in both housing starts and construction employment, and all bottlenecks were resolved. This suggests the existence of another strong mechanism that overcame the negative bottleneck effects on TTB dynamics during the housing bust.

The shifts in the left mass of the TTB distribution in both panels of Fig. 4 are also consistent with the bottleneck hypothesis. In the boom, the left mass shifted to the right, and most houses took longer to build. During the bust, the left mass shifted back to the left because the supply side had less trouble finding available construction workers to build houses. Nevertheless, the fat tail to the right of the TTB distribution in the bust indicates that some houses still took a long time to complete, contrary to the bottleneck hypothesis.

3.3. New house prices and their dispersion

House price data are essential to understanding the dynamics of TTB through the lens of the real-options mechanism. In this section, we present data on the house price index and its cross-sectional dispersion during the housing boom and bust. The relevant house price data are the sales

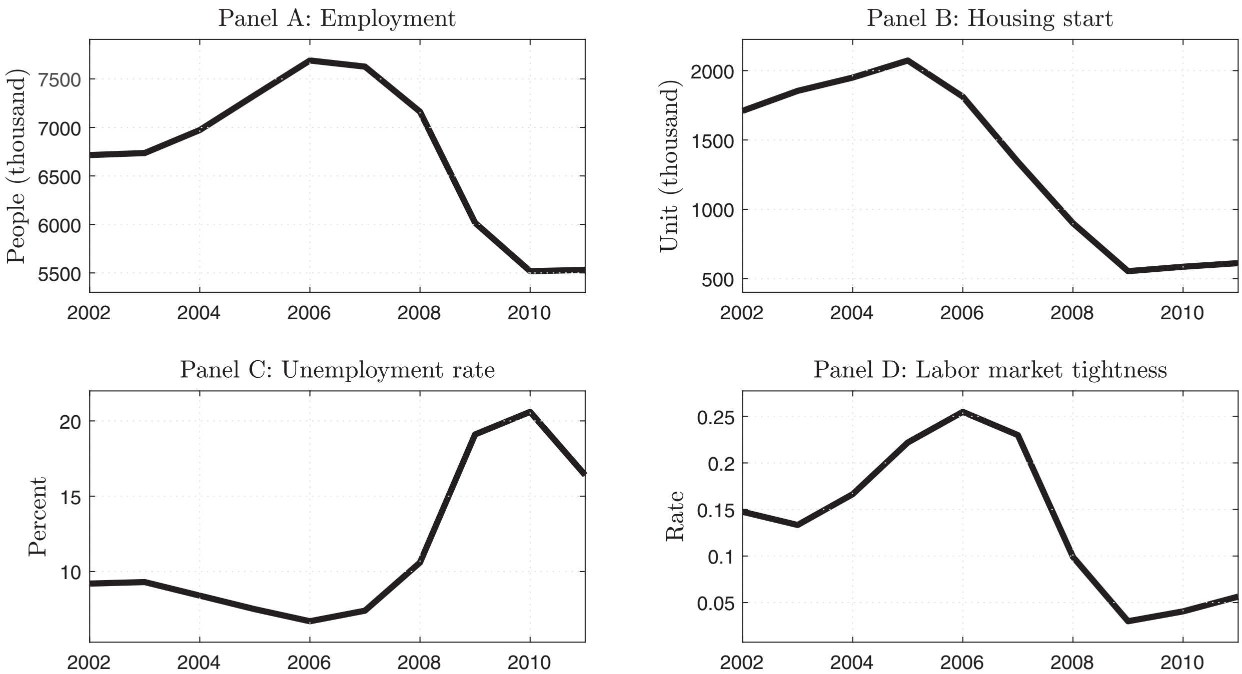

Fig. 5. Construction sector variables during the housing boom and bust. Labor market tightness is the ratio between construction job openings and unemployed people reporting previous jobs in the construction sector.

prices of new residential construction, not the prices of existing houses found in, for example, the Case–Shiller home price index. New house prices are weighted toward locations with large volumes of new construction, which have high housing supply elasticity. On the other hand, the standard repeat sales house price indices are based on existing houses, which are likely driven by locations with low housing supply elasticity. The negative relation between house supply elasticity and house prices could have generated a significant gap between new house prices and existing house prices in the recent housing cycle (Saiz, 2010).

Because our model applies to new construction, we use the new house price data. Ideally, we would construct a new house price index by comparing the prices of identical houses over time. However, quality adjustment is challenging for new construction as repeated sales are not observed. The best data available for the time series of quality-adjusted new house prices are from the Census Bureau. Based on the same Survey of Construction data, the Census Bureau computes the price index of all new single-family houses sold. That is, in each year and region, it performs separate hedonic regressions of new house sales prices based on construction characteristics. Using those coefficient estimates, the Census Bureau constructs the new house price index according to a chosen base year. Data for quality-adjusted new house price dispersion can also be computed by this method. Using the log of sales price and the construction characteristics for each new house in our micro data, we follow the Census Bureau method and estimate the residuals of the hedonic regression. A detailed description of the estimation is available in the Online Appendix. New house price dispersion in each period is the variance of these estimated residuals.

Fig. 6 plots both the new house price index (deflated by the Consumer Price Index for all items less shelter) and the (quality-adjusted) new house price dispersion during the housing boom and bust. The new house price index was high during the boom and low during the bust. The movement of this price index is smaller than that of the Case–Shiller index (also deflated by the Consumer Price Index for all items less shelter). The high housing supply elasticities for new construction locations could contribute to this price growth gap between the two indices. The new house price dispersion was high during the boom-bust period, with its peak in 2008.

4. Model simulation and estimation

In this section, we simulate and estimate the homebuilder model in Section 2 using the data in Section 3 to study the dynamics of TTB investment with regard to bottlenecks, prices, and uncertainty. While bottlenecks and house prices are key forces driving investment, our model abstracts from other potential channels that could also affect TTB, such as demand shifts beyond those reflected in house price dynamics or financial frictions. Our model estimates should be considered the first step toward understanding TTB investment dynamics. We describe the simulation and estimation steps below, with additional details provided in the Online Appendix.

4.1. Simulation details

The economy in each regime consists of 20 thousand builders. Each builder solves the Bellman equation described in Section 2, extended to incorporate aggregate un-

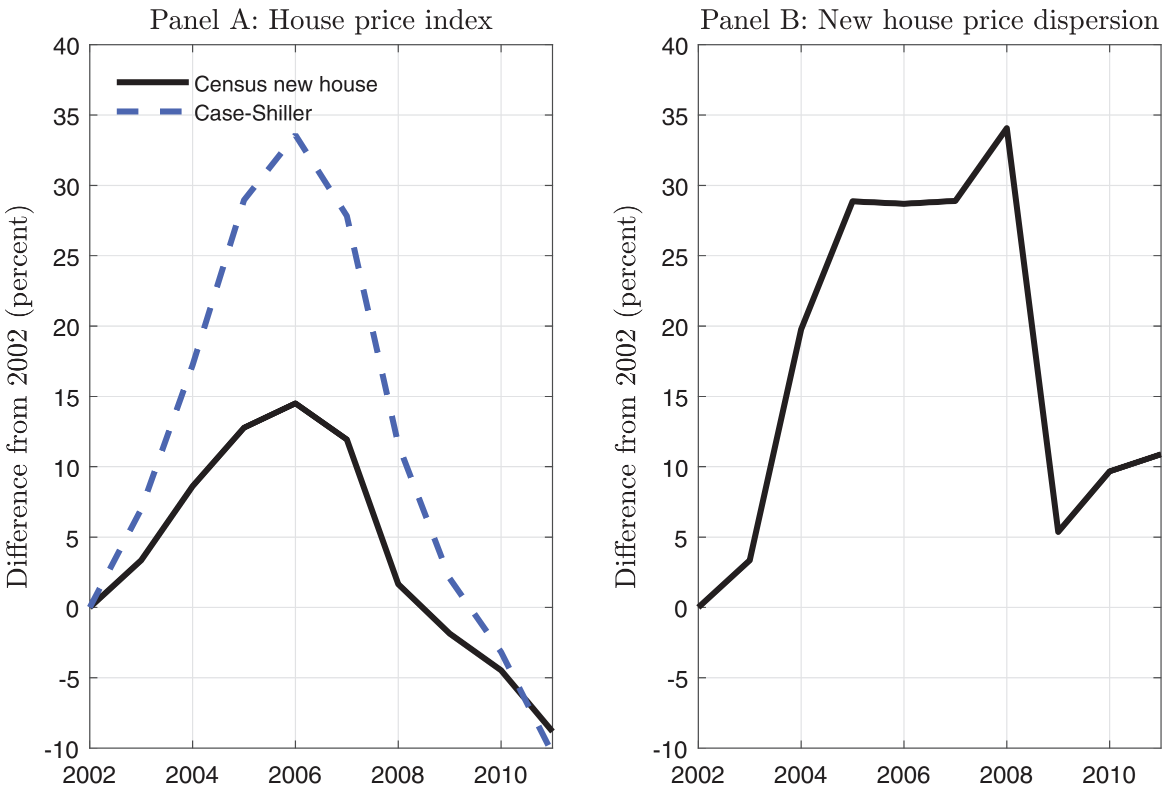

Fig. 6. House price index and dispersion during the housing boom and bust. "Census new house" indicates the Census Bureau price index of new single-family houses sold. "Case–Shiller" indicates the Standard & Poor's CoreLogic Case–Shiller national home price index, which is a composite of single-family home price indices for the US Census Bureau divisions. Both price indices are deflated by the Consumer Price Index for all items less shelter (data from the Bureau of Labor Statistics). New house price dispersion is the variance of residuals of the hedonic price regression used to construct the Census Bureau new house price index.

certainty over the three parameters p_c, P^M, and σ. In each period, a builder could have an incomplete building under construction. Builders without an ongoing project get a fresh price draw and decide whether to start a new building. When a project remains incomplete for 70 months, it is abandoned.[10] The builder is available for new construction only after a project is completed or abandoned.

4.2. Predetermined parameters

The model frequency is monthly. The net monthly interest rate r is set at an annualized value of 6.5% (Bloom, 2009). The overall construction cost $\bar{K}$ is normalized at one. The physical TTB constraint $\bar{K}/\kappa$ is set at four months because, in the empirical TTB distribution, less than 10% of houses are built within three months. The monthly maintenance cost m is set at an annualized value of 2%, consistent with the annual depreciation rates of residential structures reported in the Bureau of Economic Analysis. For the fixed cost of starting construction, we set $\gamma = 0.073\bar{K}$, which implies that the initial sunk cost is 6.8% of total construction spending (see Table 1).

[10] In the data, the maximum TTB observed between 2002 and 2011 is 62 months.

4.3. Estimation details

The goal in the empirical analysis is to understand the model-based drivers of TTB during the housing boom and bust period. The model uses three key governing values: the bottleneck effect (p_c), the price effect (P^M), and the uncertainty effect (σ). We use our micro-data to estimate the structural channels of the model and to determine whether uncertainty effects played a distinctive role during the housing cycle.

We apply the model to the years between 2002 and 2011 using the simulated method of moments estimation, in which observations in each completion year are treated as outcomes from a separate regime. Thus, we simulate and estimate ten regimes using the empirical moments of completed houses in each year. In each regime, we assume the following stochastic processes for the three aggregate variables:

$$log(p_{c,t}) = log(p_{c,t-1}) - \frac{\sigma_{p_c}^2}{2} + \sigma_{p_c} W_{p_c,t}, \quad W_{p_c,t} \sim N(0,1), \tag{10}$$

$$log(P_t^M) = log(P_{t-1}^M) - \frac{\sigma_{P^M}^2}{2} + \sigma_{P^M} W_{P^M,t}, \quad W_{P^M,t} \sim N(0,1), \tag{11}$$

$$log(\sigma_t) = log(\sigma_{t-1}) - \frac{\sigma_\sigma^2}{2} + \sigma_\sigma W_{\sigma,t}, \quad W_{\sigma,t} \sim N(0,1), \tag{12}$$

where t is monthly and the standard deviations of the processes are $\{\sigma_{p_c}, \sigma_{pM}, \sigma_\sigma\}$.[11] The builders also take into account the uncertainty of these aggregate variables when making their decisions. In the simulation, we study a path in which the realized values of these variables are constant within a regime, but different across regimes. Therefore, we estimate 30 aggregate variables $\{p_{c,T}, P_T^M, \sigma_T\}_{T=2002}^{2011}$. These values are interpreted as the average aggregate states that generate the observed statistics on completed houses in their corresponding years.

The annual growth rate of the macro price factor is set as the annual growth rate of the price index of new single-family houses sold (Census Bureau) divided by the Consumer Price Index for all items less shelter (BLS). Therefore, given an initial value P_{2002}^M, the macro price factors are predetermined.[12] The parameter σ_{pM} can also be measured by utilizing the historical series of the constructed price index. The two other parameters, σ_{p_c} and σ_σ, are not observed in the data. In the benchmark, we set $\sigma_{p_c} = \sigma_\sigma = \sigma_{pM}$. We also conducted a sensitivity analysis with different values for σ_{p_c} and σ_σ in the Online Appendix.

To estimate the aggregate variables, we minimize the following objective function. Denote the vector of empirical moments as $m^d(x)$ and the vector of simulated moments as $m^s(y;\ \Lambda)$, where x is the data sample and y is a simulated data sample under the vector of aggregate variables Λ. The vector Λ is estimated by

$$\hat{\Lambda} = \arg\min_{\Lambda}\ [m^d(x) - m^s(y;\ \Lambda)]'\ \widehat{W}\ [m^d(x) - m^s(y;\ \Lambda)], \quad (13)$$

where $\widehat{W}$ is a weighting matrix.

The aggregate variable vector is $\Lambda = \{p_{c,T}, P_T^M, \sigma_T\}_{T=2002}^{2011}$, where the price growth rate is predetermined as described above. The empirical moments used for the estimation of each year are (1) mean economic TTB, (2) $Pr(\text{economic TTB} \le 6\,\text{months})$, and (3) new house price dispersion. The lower bound of the empirical economic TTB is set at four months, consistent with the model's minimum TTB.

These moments target both the average TTB pattern in the data and the key mechanisms we are emphasizing. For the bottleneck probability, $p_{c,T}$, a frequency of economic TTB less than or equal to six months is used because construction of short duration is unlikely to be driven by other channels. Pure bottlenecks are therefore more likely to affect this moment. The new house price dispersion is used to identify σ_T.

The weighting matrix $\widehat{W}$ is chosen as the inverse of the covariance matrix of $m^d(x)$. The covariance matrix is calculated using the influence function technique described in Bazdresch, Kahn and Whited (2018). Further details on the weighting matrix and the estimation procedure are provided in the Online Appendix.

4.4. Estimation results

Table 3 reports the model parameter estimates and the standard errors. Overall, the parameters are all estimated with good precision. For the bottleneck parameter $p_{c,T}$, we find that the number peaks in 2006 and drops afterward. The bottleneck probability increases more than 20% in 2006 over its 2002 value. For the uncertainty parameter σ_T, the value increases more gradually, peaking in 2009, and remains high in 2010. Uncertainty increases by more than 20% in 2009 over its 2002 value. Moreover, both the difference between the bottleneck estimates in 2002 and 2006 and the difference between the uncertainty estimates in 2002 and 2009 are statistically significant, as the 95% confidence intervals of the two years for each parameter do not overlap.

Table 3
Model parameter estimates and standard errors. The formula used to compute the standard errors is provided in the Online Appendix.

Parameter	Year	Estimate	Standard error	95% confidence interval
P_T^M	2002	2.098	0.00754	2.084, 2.113
$p_{c,T}$	2002	0.337	0.00257	0.332, 0.342
	2003	0.341	0.00264	0.335, 0.346
	2004	0.354	0.00255	0.349, 0.359
	2005	0.384	0.00243	0.379, 0.389
	2006	0.417	0.00247	0.412, 0.421
	2007	0.411	0.00276	0.405, 0.416
	2008	0.397	0.00367	0.390, 0.404
	2009	0.303	0.00458	0.294, 0.312
	2010	0.256	0.00528	0.246, 0.266
	2011	0.281	0.00557	0.270, 0.292
σ_T	2002	0.398	0.00299	0.392, 0.404
(annual)	2003	0.412	0.00344	0.405, 0.418
	2004	0.438	0.00269	0.433, 0.443
	2005	0.444	0.00316	0.438, 0.450
	2006	0.448	0.00380	0.440, 0.455
	2007	0.471	0.00334	0.464, 0.478
	2008	0.466	0.00415	0.458, 0.474
	2009	0.484	0.00341	0.478, 0.491
	2010	0.458	0.00420	0.450, 0.466
	2011	0.405	0.00380	0.398, 0.413

Fig. 7 reports the target moments for both the data and the estimated model. The model fit of the estimated values is good across the distributional moments in each year. The estimated model is consistent with the dynamics of mean TTB and its density below six months. The estimated model also matches the level and the time series pattern of the price dispersion well.

To understand the estimated channels of TTB dynamics, we compute the historical decomposition of TTB with regard to the evolution of the three estimated structural parameters. Because the solution of the model is nonlinear, the effect of each channel can be gauged in two different ways. For example, when computing the price effect, we could fix $p_{c,T}$ and σ_T at their respective 2002 values and plot the time series of the annual mean TTB when only prices change. Alternatively, we could fix P_T^M at its 2002 value and plot the implied annual mean TTB dynamics as the other values change across time. Subtracting this counterfactual value from the model-estimated mean TTB would provide the net price effects. Panel B of Fig. 8 reports the average of these two methods of computing the historical decomposition.

Several results are worth noting. First, the increase in TTB up to 2007 is driven mainly by the bottleneck effect. Although the increase in uncertainty also mildly increases

[11] The bottleneck probability $p_{c,t}$ is also bounded above by one.
[12] This lowers the computational burden in the estimation process.

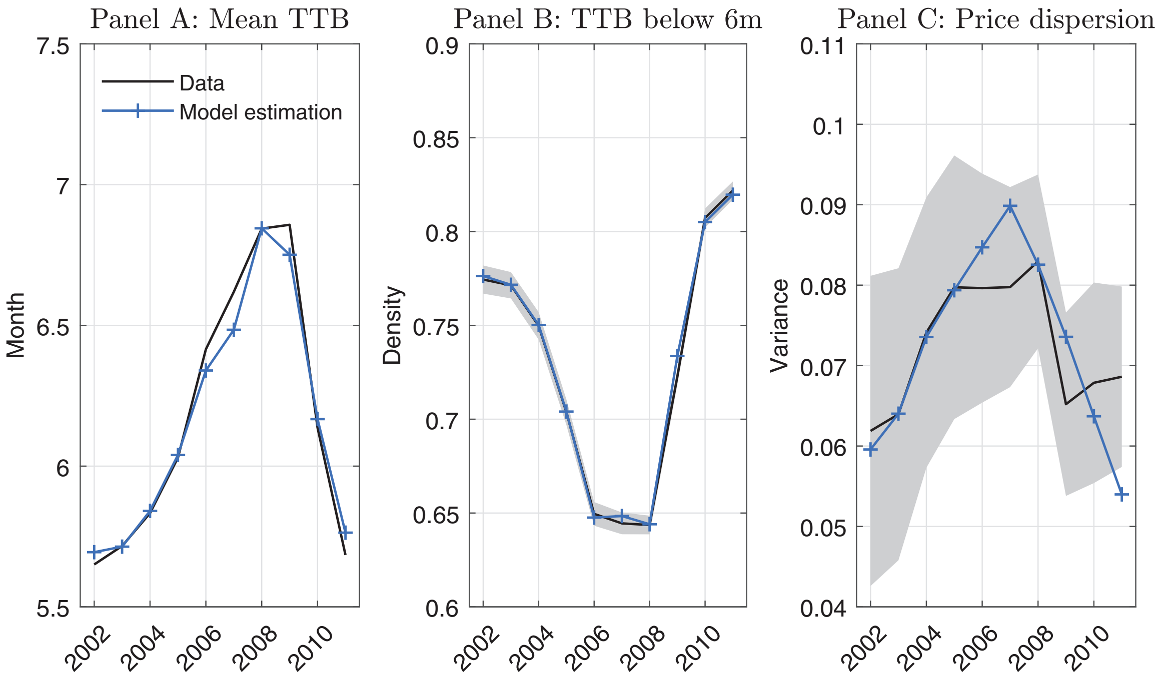

Fig. 7. Simulated method of moments (SMM) model fit. The three moments (other than the new house price index) used in the estimation of parameters for each year are plotted. The black solid lines are the empirical moments with 95% confidence intervals shaded in gray, and the blue solid lines with markers are the estimated moments using SMM. The 95% confidence interval for mean time to build is tight and not visible in Panel A. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

TTB during this period, the large increase in house prices counters that increase.[13] Second, the further increase in TTB in 2009 is no longer driven by bottleneck effects. The model estimates suggest that all bottlenecks were resolved in 2009. Therefore, the estimated model is consistent with the view that bottleneck effects are not the driving force of TTB dynamics during the housing bust. The overall pattern of the bottleneck parameter in Panel A of Fig. 8 aligns well with the tightness of the construction sector labor market variables shown in Fig. 5. While the construction sector labor market tightness has not been used in the estimation, the similarity between the pattern of the tightness measure and the estimated bottleneck channel suggests that the two could be closely linked. Third, with small price effects, the uncertainty effect dominates TTB variation in the housing bust. In 2009, the uncertainty effect generates most of the increase in TTB.

4.5. Relation with other uncertainty measures

By estimating uncertainty shifts over the most recent housing boom and bust, we contribute to the business cycle literature on the measurement of time-varying uncertainty. In Fig. 9, we plot our uncertainty estimate on top of the three-month-ahead macroeconomic uncertainty measure used in Jurado, Ludvigson and Ng (2015). The measure is computed by first taking the conditional volatility of the purely unforecastable component of the three-month-ahead value of each individual economic time series and then aggregating individual uncertainty at each date.

The increase in uncertainty during the Great Recession relative to 2002 is quantitatively comparable to the result in Jurado, Ludvigson and Ng (2015). At the same time, our estimate remains high during the boom and after the bust, whereas the macroeconomic uncertainty measure remains closer to its 2002 value in other years. Our uncertainty estimate is based purely on residential construction and new house price data, and the macroeconomic uncertainty measure in Jurado, Ludvigson and Ng (2015) uses 132 individual macroeconomic series. Because the housing market peaked earlier and underwent a slower recovery than the macroeconomy did, uncertainty surrounding the construction industry could have also been high for a longer period. Moreover, the higher housing market uncertainty in 2004–2005 is consistent with the increasing housing demand due to the expansion of subprime loans in the mortgage market. The increase in high-risk mortgage loans in this period could have led to higher demand uncertainty across the different houses the builders had completed.

5. Housing supply implications

The results so far imply that the real-options mechanism can account for a significant portion of the TTB dynamics in the most recent housing bust, even though TTB is assumed to be fixed in standard business cycle studies

[13] Although we control for housing quality, the estimated increase in uncertainty during the boom is still consistent with the increase in overall house price dispersion shown in Van Nieuwerburgh and Weill (2010).

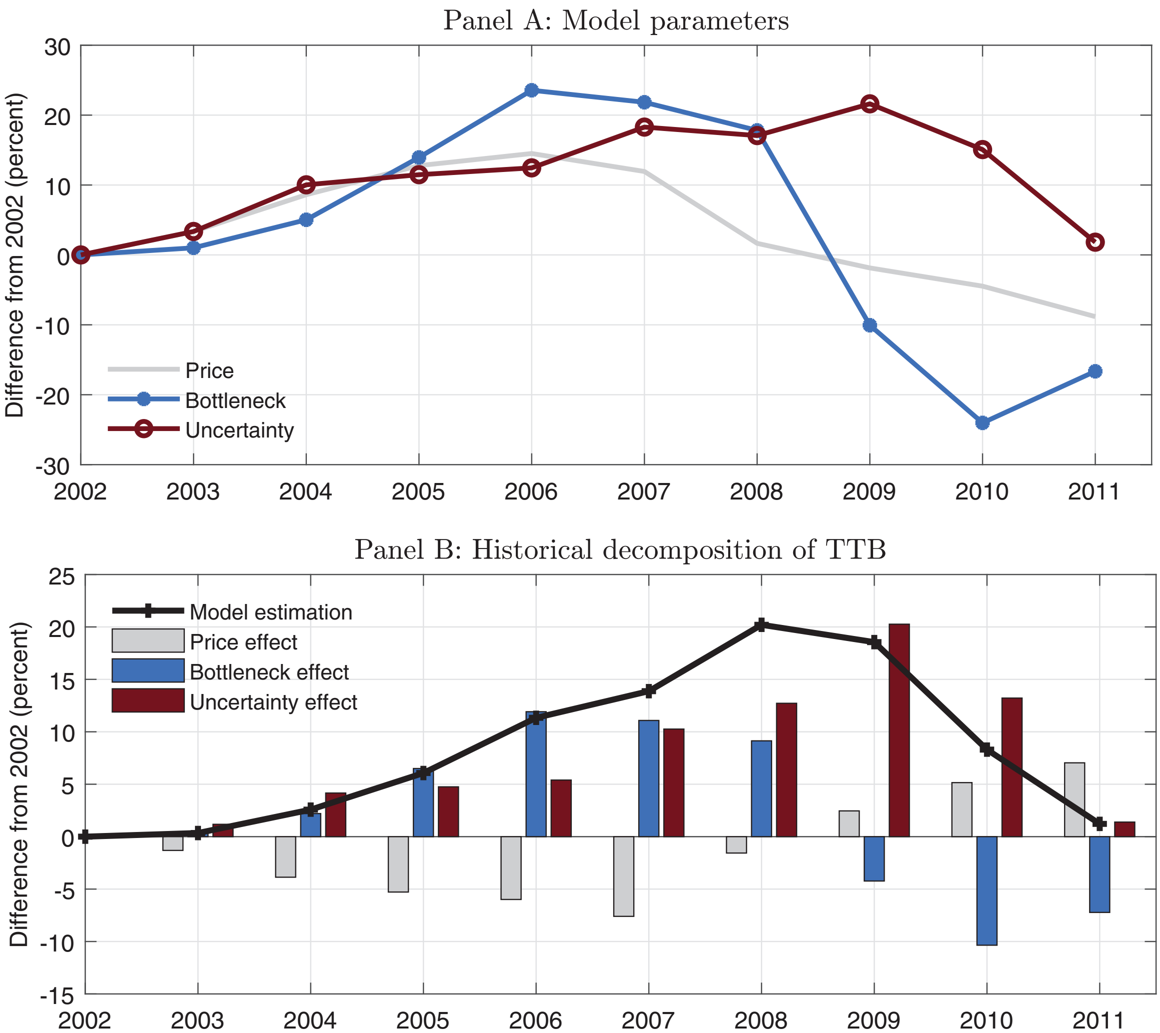

Fig. 8. Simulated method of moments parameters and historical decomposition of time to build (TTB). Panel A plots the estimated parameters (bottleneck and uncertainty) relative to the first year in percentage terms. The price series is the newly sold house price index (from the Census Bureau) deflated by the Consumer Price Index for all items less shelter (from the Bureau of Labor Statistics). Panel B plots the estimated mean TTB and the historical decomposition of TTB variation relative to its 2002 value.

(Kydland and Prescott, 1982). In this section, we use our simulation to consider the housing supply implications that follow from the real-options channel of TTB. We study the model's implications for housing starts and residential investment.

To isolate our model channels, we also solve a counterfactual fixed TTB model in which TTB is delayed only by bottlenecks and builders with ongoing construction must continue investment until completion. We consider how the real-options TTB channels account for the housing start and residential investment dynamics in the most recent housing cycle. Residential investment includes both extensive (housing starts) and intensive (TTB) investments.

Fig. 10 plots the implied housing supply variables in both models: the implied housing starts and residential investment based on all three parameters, along with housing starts and residential investment data for single-unit houses. Based on 2002, the model claims a 27% to 29% decline in housing starts and residential investment in 2009. The fixed TTB model shows an 11% decline in housing starts and residential investment in the same year and a quicker recovery than the real-options TTB model shows. The gap in housing starts between the two models arises only in 2008 and afterward, when the price is low and uncertainty peaks.

In the data, housing starts and residential investment fell by 68% in 2009 and remained low afterward. The real-options TTB investment channel generates a slump in housing starts and residential investment, which is closer to the data than the fixed TTB model. Our model accounts for about 40% of the observed decline in housing starts. However, our model is limited in two dimensions. (1) It cannot account for the remaining 60% of the decline in housing starts, and (2) housing starts in our model decline in the housing boom period. Similar arguments apply to residential investment.

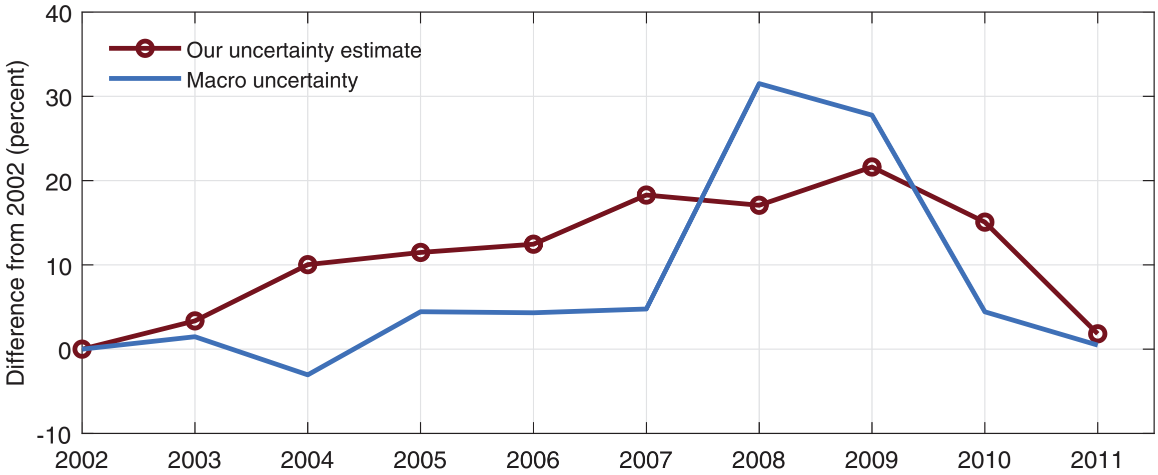

Fig. 9. Measures of uncertainty. Macro uncertainty plots the three-month-ahead uncertainty measure (averaged within each year) used in Jurado, Ludvigson and Ng (2015). Both measures are plotted relative to their respective 2002 values.

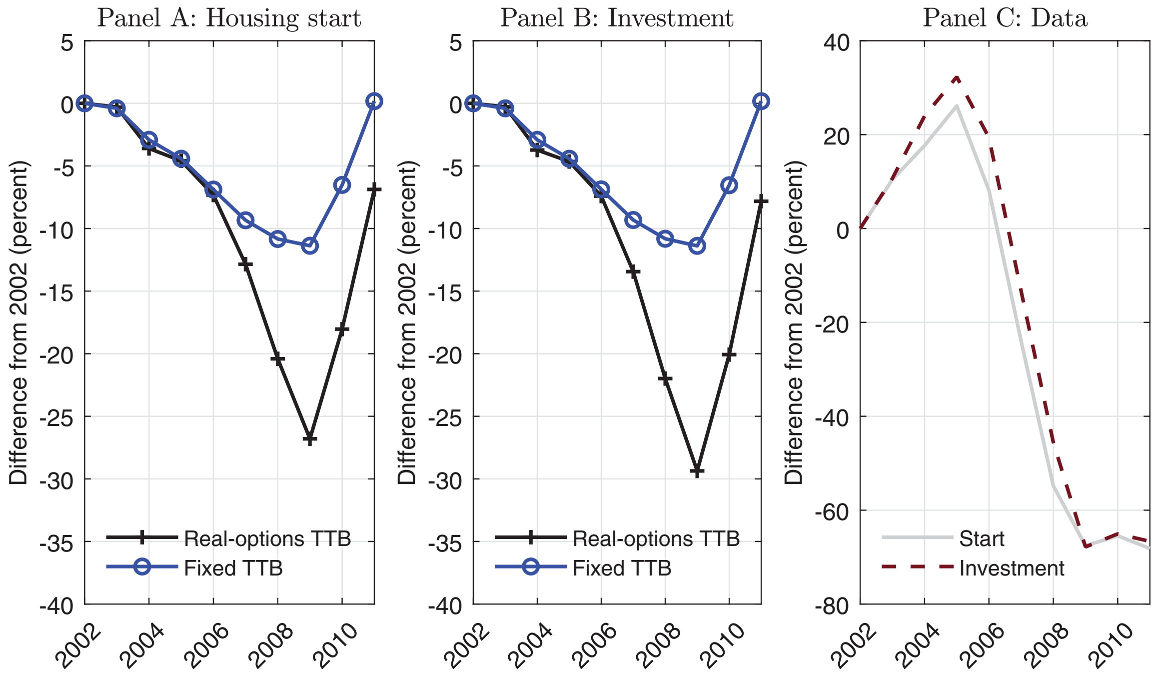

Fig. 10. Housing supply model and data. The figure plots housing starts and (residential) investment for both models with all three parameters in effect and the data. Real-options time to build (TTB) indicates our model and fixed TTB indicates a model in which TTB is delayed only by bottlenecks. Housing start data come from the Census Bureau series “Privately owned housing starts: 1-unit structures.” Investment data come from the National Income and Product Accounts series “Real private fixed investment—residential structures—permanent site—single family”.

In short, although our model is estimated to match the intensive investment distribution of residential construction, it has limited influence on generating the observed housing start dynamics. The model is missing many variables that also affected housing starts in the boom-bust period. For example, the credit boom and bust would have affected the initial availability of construction loans, which could work disproportionately at the extensive margin, and the permit process could also have changed during this period. Moreover, a micro-founded model of bottlenecks during the housing boom period would imply that bottlenecks increased because builders engaged in multiple projects at the same time with an increase in housing starts during the boom, which our stochastic bottleneck assumption does not allow. Lastly, a general equilibrium model would imply that interest rates should also interact with prices and uncertainty (Bloom, Floetotto, Jaimovich, Saporta-Eksten and Terry, 2018). Interest rate movement can thus be an important channel affecting housing starts and investment decisions.

6. Conclusion

We provide new findings about the distribution of residential TTB across the US. The decrease in economic activity during the most recent housing bust is not limited to housing starts but includes TTB investment. Contrary to the notion that ongoing projects are costly to stop, we find that a significant portion of them were deferred during the housing bust. We study a model in which TTB investment responds to prices, uncertainty, and bottlenecks and simulate that model using the observed house price dynamics. The real-options mechanism can account for the decrease in TTB investment during the housing bust.

In this paper, we abstract from the searching and matching channels of housing demand to focus on supply-side decisions. We also set aside the financial frictions channel in TTB investment projects. The construction sector is a leveraged industry, and the most recent housing boom-bust cycle is closely related to the availability of credit. Builders and lenders with different financing conditions and contracts would have behaved differently during the housing bust, and the overall financial constraints could have exacerbated the aggregate housing market collapse.

Although we find that the real-options mechanism can account for investment activity in incomplete projects, its potential interactions with housing demand or developers' financial frictions are interesting extensions that should be pursued further. Room for improvement exists in ways of accounting for the housing start dynamics during the most recent housing cycle.

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