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# A spatio-temporal-similarity and common factor approach of individual housing prices: the impact of many small earthquakes in the north of the Netherlands<sup>1</sup>

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## Abstract

This paper contributes to the literature on the explanation of housing prices and the impact of many but small induced earthquakes due to gas extraction in several ways. First, our proposed methodology accounts for both local spatial dependence and common factors, also known as weak and strong cross-sectional dependence, using individual data of more than 200,000 transactions in the three most northern provinces of the Netherlands over the period 1993-2014. Second, the selection of houses within each focal house's submarket is, in contrast to previous studies, not only based on distance and time, but also on their degree of similarity. Third, we control for both non-observable and observable common factors, among which are respectively economic business cycle effects and population decline. Fourth, we accumulate the strength and frequency with which earthquakes affect each focal house before it was sold into one single measure using a seismological model and then subdivide it into different segments so as to be able to account for non-linear effects and to determine a threshold below which they have no effect. Using these techniques, we are able to investigate the propagation of the detrimental impact of earthquakes on housing prices over space and time without the need to select reference areas in advance, which potentially might also have been affected by earthquakes. It is found that housing prices started to decrease by 3.0% in 2009, by 5.2% in 2012, the year in which the heaviest earthquake occurred up to now, and finally by 9.3% in 2014.

*Keywords:* Housing prices, spatio-temporal hedonic models, earthquakes

*JEL classification:* C21, R21, R23, R31.

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## 1. Introduction

The largest natural gas field in Europe is located in the north of the Netherlands. Its exploitation started in 1963 and since then gas extraction has increased almost continuously to 2013 (Bourne et al., 2014). In January 2013, a few months after the heaviest earthquake of 3.6 on the Richter scale up to now,<sup>2</sup> the Dutch government (Kamp, 2013, p.443) formally declared that this extraction has induced many small earthquakes in eight municipalities located in the province of Groningen due to induced soil compaction. Although these earthquakes do not pose the threat of a catastrophe, there are indications that their increasing frequency and magnitude have affected the market value of houses located in the region. However, there is uncertainty and debate since when and also until where the affected area extends. Even though the gas-extracting company (NAM<sup>3</sup>) has been mandated to compensate physical damages caused to houses (according to the Mining Act approved in 2003, see Roggenkamp, 2016), and anticipated increases in house maintenance costs should therefore not affect its price, an additional and significant financial loss due to market value depreciation may be expected. Furthermore, while in line with this Mining Act a committee was created to advise citizens who wish to claim compensation for damages (Roggenkamp, 2016), this opportunity has hardly been used until 2012. Shortly after the government declaration, the NAM established a new claimant procedure, which resulted in a boost of the number of claims but which the afflicted households nonetheless experience as insufficient and time consuming (Van der Voort and Vanclay, 2015). Consequently, transaction costs caused by this claimant procedure (bureaucracy, troubles, visits of surveyors) are also likely to have a price reducing effect.

As from April 2014 NAM also started compensating market value depreciation.<sup>4</sup> Providing an accurate estimate is therefore a relevant but also a difficult policy issue. In this paper we try to estimate this effect employing space-time specifications of hedonic models for real estate markets. These models identify the marginal willingness to pay for each characteristic of the house and each local amenity provided at its location or, alternatively, the marginal compensation for each disamenity, as originally proposed by Rosen (1974). Seismic activity may be considered such a price-reducing disamenity, which in this particular case can be best identified by the effect on houses sold up to and including 2014, i.e., before the NAM introduced the compensation scheme for non-material damages.

This paper contributes to the hedonic house price literature in several ways. The first is that our econometric approach accounts for both local spatial dependence and common factors, also known as weak and strong cross-sectional dependence (Chudik et al., 2011). Bailey et al. (2016a) is one of the first studies combining both types

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<sup>2</sup>On August 16, 2012, in Huizinge.

<sup>3</sup>Nederlandse Aardolie Maatschappij (NAM) is a joint venture between Anglo-Dutch Shell and ExxonMobil, with headquarters in the city of Assen, the capital of the Dutch province of Drenthe.

<sup>4</sup>In September 2015, a Dutch court in Assen ruled for around 900 private households and 12 housing corporations to be compensated by NAM for non-material damage. More recently, the court ruled in favor of compensation of homeowners due to stress caused by earthquakes in the region.

of dependence in one framework, but in contrast to this study we use individual rather than aggregated data, and a simultaneous rather than a two-stage approach. Furthermore, in contrast to previous studies focusing on weak cross-sectional dependence only (in some parts of the literature better known as spatial dependence), the selection of houses that will be used to explain the price of the focal house will be based not only on distance and time but also on their degree of similarity. Another contribution is that we control for both observable and non-observable common factors, among which are respectively population decline and economic business cycle effects. The final contribution is that we accumulate the strength and frequency with which earthquakes affect each focal house before it was sold into one single measure using a seismological model, building upon previous research of Koster and Van Ommeren (2015). Next, we split up this variable into different segments, thereby following Atlas voor Gemeenten (2017) and Cheung et al. (2018), to allow for non-linear effects. In addition, it is investigated whether this measure first needs to exceed a certain threshold before it starts to have an effect on housing prices. These three contributions are more detailed below.

Testing and accounting for cross-sectional dependence when evidence is found in favor of it has become a major research area in the econometrics literature. If a house is put for sale on the market and the owner or real estate agent uses information of houses with similar characteristics that are for sale or have been sold in the past to set the asking price, then individual housing prices will no longer be independent of each other. This is known as the sales comparison approach and also reflects the price-setting behavior of realtors in the Netherlands (Op't Veld et al., 2008). Similarly, if a potential buyer is shopping around within a particular search area and is comparing the best possible set of housing characteristics given his budget, bids for any house will depend on the asking price and characteristics of other houses. This property that individual observations may not be treated independent of each other is known as local spatial dependence or weak cross-sectional dependence. To adequately account for this type of dependence, observations on individual houses are required. A seminal paper in this respect is of Pace et al. (1998) since they compute spatial and temporal weight matrices to determine the effect of predated and nearby price transactions onto the focal house. Many studies have followed this basic modeling setup and will be briefly discussed in Section 2. Gibbons and Overman (2012) argue that spatial econometric models may suffer from misspecification since the weight matrix which is central to those models is constructed in an ad-hoc manner. However, one issue often overlooked here is that weight matrices when explaining housing prices can only be constructed in a meaningful way when employing data on individual houses. Many non-spatial but also spatial hedonic studies in the literature employ data aggregated at some spatio-temporal scale (e.g., average prices per municipality, zip-code, or neighborhood, on a monthly, quarterly, or yearly basis). However, as every house is sold within a specific spatial and temporal context, each focal house's submarket defined by similar nearby and previously sold houses needs to be accounted for.

Jansen et al. (2016) compare 13 models with each other that have been used or proposed to study the impact of earthquakes on housing prices in the north of the Netherlands. None of them has used spatial econometric methods up to now. On the basis of this overview, the authors recommend to further explore this method (p.96).

This study fills this gap. In contrast to previous spatial econometric studies, the selection of houses applied in this study is not only based on distance and time within each focal house's submarket, but also on their degree of similarity, using an index developed by Op't Veld et al. (2008) that will be explained in more detail in Section 3. Another issue is that the transaction price of a house is not only taken to depend on houses that have been sold before the asking price is set, but also by similar houses that have been for sale contemporaneously since they are competitive alternatives for searching buyers and therefore may also affect its transaction price. For this reason, we extend previous studies by considering one spatio-temporal-similarity matrix weighting houses according to how relevant they are in the asking price-setting procedure, and another spatio-temporal-similarity matrix weighting houses that are sold during the time each individual house is on the market.

A complication is that housing values might also be going up or down due to external factors. These factors affect the price of every transaction at the same moment in time, though not necessarily to the same extent, which points to correlation due to common factors, i.e., prices correlate independently of any distance decay effects, also known as strong cross-sectional dependence. One such common factor are business cycle effects, which are usually controlled for by time-period fixed effects in the real estate literature. However, Halleck-Vega and Elhorst (2016) and Shi and Lee (2017) point out this is not more than a special case of a much wider class of models controlling for strong cross-sectional dependence. Following Pesaran (2006), the former study suggests to add time-specific cross-sectional averages of the dependent variable to the model and to allow the coefficient of this variable to vary across space. This relatively advanced approach to control for so-called non-observable common factors will also be adopted in this paper.

To identify the impact of earthquakes we rely on the earthquake's Peak Ground Velocity (PGV) at each house's geographical location (latitude and longitude) using a seismological model. Koster and Van Ommeren (2015) also employ this measure but only count earthquakes that can be felt (i.e.  $PGV > 0.5$  cm/s). By contrast, we construct a variable summing up the impact of every single earthquake, so as to also account for differences in the intensity of the earthquakes. To determine the impact of earthquakes and to control for common factors, many studies (four studies relevant in this context, though published in Dutch, are Francke and Lee (2013), Bosker et al. (2016), Atlas voor Gemeenten (2017), and CBS (2017)) do not employ any earthquake measure but instead compare the development of housing prices in the area formally labeled as being subject to earthquakes and a selection of reference areas or reference houses not affected by earthquakes with (almost) similar background statistics.<sup>5</sup> However, since the actual area affected by earthquakes is unknown and therefore needs to be determined<sup>6</sup>, approaches based on measures trying to determine the intensity and frequency of earthquakes at different locations are more fruitful. It avoids selecting areas that have actually been affected, or were so in

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<sup>5</sup>The latter three studies also do some simple robustness checks based on Koster and Van Ommeren's PGV measure or based on damage claims to differentiate the impact on housing prices within the boundaries of their risk area.

<sup>6</sup>Many house owners outside the formal earthquake area also claim damages and financial losses due to earthquakes.



the course of time since the affected area tends to expand.

Compared to Koster and Van Ommeren (2015), this study also employs data pertaining to a wider research area. To be able to account for earthquakes and to avoid that the impact of both observable and non-observable common factors be erroneously assigned to earthquakes, the research area should be wider than just the province of Groningen, where the major gas well is located. For this reason, we also collected data in Groningen's two neighboring provinces Friesland and Drenthe. Furthermore, we employ data over a longer time period (1993-2014 instead of 1996-2013) and control for more characteristics of the house and the neighborhood in which it is located (81 in total instead of 18). These extensions have major effects on the estimation results.

The paper proceeds as follows. Section 2 provides a brief literature overview of the effect of amenities and disamenities on housing prices and on spatio-temporal modeling of real estate markets. Section 3 details the data employed, the measurement of earthquakes, the spatio-temporal-similarity weight matrices that are used in this study, and the econometric specification. Section 4 reports and discusses the main empirical findings, while Section 5 outlines a compensation scheme based on these results. Finally, Section 6 concludes.

## **2. Literature Review**

Hedonic models identify the marginal willingness to pay for each house characteristic and local amenity or the required marginal compensation for each disamenity at its location. They are widely employed to determine the welfare effects of local public goods provision, and local amenities or disamenities. Examples are the effect of crime and immigration (Bishop and Murphy, 2011; Gautier et al., 2009), exposure to road and railway noise (Andersson et al., 2010), new construction of low-income housing (Funderburg and MacDonald, 2010), quality of schools (Fack and Grenet, 2010), housing renovations (Billings, 2015), cultural heritage (Koster et al., 2016), environmental quality (Hanna, 2007), and the proximity of industrial sites (De Vor and De Groot, 2011).

The literature on the effect of hazardous events on housing prices is also extensive. Muehlenbachs et al. (2015) estimate the impact of underground water contamination by shale gas developments on houses sold in U.S. state of Pennsylvania. They find that groundwater-dependent houses are sold for lower prices if closer to a gas well, while piped-water homes exhibit small but positive impacts, suggesting benefits from land-lease payment. Similarly, Gawande and Jenkins-Smith (2001) estimate the effects of perceived risks on residential property values of locations near a road transited by nuclear waste transporters in South Carolina. A couple of Dutch studies address the impact on housing prices, insurance premiums, and capital accumulation of being located in areas prone to be flooded since a large part of the Netherlands is located below sea level (Ermolieva et al., 2017; Votsis and Perrels, 2016). In addition to the aforementioned studies on the impact of induced earthquakes, there are also many studies on natural ones, among which Brookshire et al. (1985), Murdoch et al. (1993), Willis and Asgary (1997), Nakagawa et al. (2007), and Naoi et al. (2009).

The spatial econometric literature has consistently found empirical evidence in favor of local spatial depen-

dence in hedonic house price models, and that marginal valuations of (dis)amenities are biased if this type of weak cross-sectional dependence is not accounted for (Kim et al., 2003; Brasington and Hite, 2005; Anselin and Lozano-Gracia, 2008; Cohen and Coughlin, 2008; Leonard and Murdoch, 2009; Mínguez et al., 2012; Baltagi and Li, 2014; Baltagi et al., 2015). In addition to local spatial dependence, housing prices might be going up and down all together due to external factors, known as common factors or strong cross-sectional dependence. To test for both weak and strong cross-sectional dependence in a pseudo balanced panel of average house prices obtained by aggregating over 363 U.S. metropolitan statistical areas (MSAs) over the period 1975Q1-2010Q4, Bailey et al. (2016a) apply two statistics that have been developed to test for this: the cross-sectional dependence (CD) test of Pesaran (2004, 2015) and the exponent  $\alpha$ -estimator of Bailey et al. (2016b) measuring the degree of distance decay effects over space. Elhorst and Durán (2017) modify these tests such that they can also be applied to an unbalanced panel of individual housing prices, and apply these tests to 163,323 housing transactions that took place in the north of the Netherlands over the period 2003-2014. Both studies find strong empirical evidence in favor of both types of cross-sectional dependence. The results of these tests applied to the data set used in this paper will be presented in Section 4.

The source of the spatial dependence observed in so many studies is summarized by Brasington and Hite (2005) and Kelejian and Piras (2017, p.13). The spatial lag of the dependent variable measuring house prices captures the extent to which the price of a house is affected by the price of houses surrounding it. This lag is motivated by the fact that the asking price is often set with the knowledge of the transaction prices of similar houses in the neighborhood. Op't Veld et al. (2008) document this behavior for NVM realtors in the Netherlands. The NVM assists their clients by forecasting the price of every single house using a hedonic price regression that is ran based on data from a selection of similar nearby and previously sold houses. Spatial lags of the explanatory variables, the structural housing characteristics and local (dis)amenities of houses surrounding the focal house, may also influence its price. If a house is the largest or the smallest on the block or if surrounding houses are atypical, it often needs to be sold at a discount. Spatial lags in the explanatory variables may also cover spillover effects due to differences in local (dis)amenities. If a house is surrounded by similar houses closer located to better schools, parks, sport facilities, this might positively affect the price of the focal house. Hence, accounting for the impact of similar nearby and previously sold houses is required on penalty of ending up with biased results.

A relevant strand of literature in this respect are studies using spatio-temporal models to explain housing prices. These studies combine the micro approach used by realtors to assist their clients with the macro approach used in so many non-spatial studies to study the effect of housing characteristics and neighborhood (dis)amenities. This literature has persistently shown that spatio-temporal models significantly improve the predictive power of hedonic price equations. One of the first papers in this field is Pace et al. (1998). They compute a mix of spatial and temporal weight matrices to determine the effect from predated and nearby price transactions onto the focal house, and estimate their hedonic price equation by OLS, which is consistent due

to the recursiveness of the lower triangular structure of the employed matrices. The latter point has recently been made again by Bhattacharjee et al. (2016). In a similar type of study, Pace et al. (2000) find that a model with spatial, temporal, as well as both spatial-temporal and temporal-spatial interactions in the error terms outperforms a traditional hedonic model with 122 housing characteristics and including space and time indicator variables. Just as these previous two studies, Smith and Wu (2009) allow for both spatio-temporal lag effects by assuming that there is some threshold time interval and some threshold distance beyond which other housing sales have no direct influence on the price of the focal house. In addition, they assume that the error terms follows a first-order autoregressive process with unequally spaced serially lagged terms depending on the time that previous sales occurred. In this study we try to disentangle the effects from transactions that occurred before the focal house was put for sale from transactions taking place within the period it was on the market.

One recent contribution to the literature is of Füss and Koller (2016). As in previous studies, the authors develop a spatio-temporal approach to forecast housing prices; by means of a classification and regression tree method they define houses belonging to each house's sub-market. In addition, they partition the research area in several discrete sub-markets and the sample period in several discrete time intervals, so as to be able to control for sub-market and time-period fixed effects. Spatial fixed effects may control for local-specific time-invariant (dis)amenities that do affect the dependent variable, but which are difficult to measure or hard to obtain. In this paper we will also use local fixed effects to account for discrete sub-market heterogeneity. Similarly, time-period effects may control for spatial-invariant variables. As indicated in the introduction, however, a more advanced method to control for this is by adding time-specific cross-sectional averages of the dependent variable to the model and to allow the coefficient of this variable to vary across space.

### **3. Data and empirical setup**

#### *3.1. Data employed*

We employ data of 220,686 housing transactions over the period 1993 - 2014 for the three most northern provinces of the Netherlands (Groningen, Friesland, and Drenthe). Since we need data of previously sold houses to be able to construct spatio-temporal-similarity matrices, data observed in 1993 are used only for this secondary purpose. The data set was provided by the Dutch Association of Realtors (NVM), the largest association of real estate agents in the Netherlands, and contains variables on 69 housing characteristics, among which the home address. Given this address, we geo-referenced each house by adding its longitude and latitude coordinates and subsequently used this information to gather neighborhood characteristics from the Central Bureau of Statistics (CBS) in the Netherlands. Table A.1 in the Appendix provides brief descriptions of the housing and neighborhood characteristics that are used in the hedonic price regressions. In addition, we report the mean value of every variable in the data set, and the coefficient estimates and their significance levels of the model to be discussed shortly.

Data on earthquakes are provided by the Geo-services office of the University of Groningen. They assemble data collected by the Dutch meteorology institute (KNMI) of each earthquake that occurred in the Netherlands since this institute started to measure seismic events in the eighties. Between 1985 and the end of 2014 the North was hit by 663 earthquakes with a magnitude greater than 1 on the Richter scale. In the next section we explain the implementation of this information in our model setup.

### 3.2. *Measuring the effect of earthquakes*

Information about the epicenter location (geographical coordinates) and magnitude (Richter scale) of each earthquake is available with great accuracy. However, estimating site-specific ground motions at housing locations of a series of earthquakes is complicated and subject to statistical uncertainties. Attempts to develop and to estimate seismological models for the Groningen gas field have been carried out by the geologists Van Eck et al. (2006) and Bourne et al. (2014). For this purpose, they consider the Peak Ground Velocity (PGV). An earthquake's PGV at any given location is a function of its magnitude, depth, and distance to its epicenter and an error term for unknown factors omitted from the model (Dost et al., 2004). In the concluding section we come back to recent attempts to improve these functional forms. Koster and Van Ommeren (2015) employ the PGV variable to count the number of earthquakes that can be felt, being the area of locations at which the ground motion is still greater than at least half a centimeter per second (0.5 cm/s) and at each site of those houses that were for sale at a particular point in time. However, it is questionable whether the use of a discrete variable counting the number of earthquakes that could be felt fully addresses the type of information searching buyers might have used to decide whether or not to buy a house. They might also have been guided by the magnitudes of earthquakes. Furthermore, even if a house has not been hit by any earthquake that could be felt, it might be perceived as equally prone to receiving earthquakes as houses located in the neighborhood that have been hit before, for example, due to the large number of earthquakes that reached that house that could not be felt. It is also not certain whether searching buyers are only guided by earthquakes that could be felt. Moreover, Van Eck et al. (2006) state that people are sometimes also able to feel earthquakes of 0.2 cm/s. Finally, it is unlikely that the value of a dwelling decreases proportionally with the number of earthquakes, since it would imply that its value may potentially fall below zero. Consequently, while PGVs provide an integral and comprehensive measure to assess the magnitude with which an earthquake hits a house, counting the number of earthquakes that could be felt at a particular house may not be the best variable to determine the effect of those on its price. Therefore, rather than computing a discrete variable counting the number of earthquakes that could be felt, we accumulate the PGVs at the location of the house from all earthquakes stronger than 1 on the Richter scale that took place before the house was sold.

Consider a house  $i$  sold at time  $t$ , and an earthquake  $j$  occurring at time  $\tau < t$ , with magnitude  $M_j$ , at  $s_j$  kilometers of depth from the surface and at a distance of  $d_{ij}$  kilometers. Then the PGV of earthquake  $j$  on house  $i$  can be computed as follows (Dost et al., 2004; Koster and Van Ommeren, 2015; Atlas voor Gemeenten,

2017):

$$\log_{10} v_{ji} = -1.53 + 0.74M_j - 1.33 \log_{10} r_{ji} - 0.00139r_{ji}, \quad (3.1)$$

where  $v_{ji}$  is the PGV in cm/s of earthquake  $j$  on house  $i$ , and  $r_{ij} = \sqrt{s_j^2 + d_{ij}^2}$  is the hypo-central distance (km) between the epicenter and the house. After computing the PGV of every earthquake onto each house, a matrix of order  $220.686 \times 663$  is obtained with typical element

$$v_{ji} = \begin{cases} 10^{-1.53+0.74M_j-1.33 \log_{10} r_{ji}-0.00139r_{ji}} & \text{if } \tau < t \\ 0 & \text{otherwise.} \end{cases} \quad (3.2)$$

The natural log of every row sum of this matrix represents the total PGV (denoted by  $e_i$ ) received by a particular house  $i$  from every earthquake prior to its transaction date. It represents the basic measure to assess the impact of earthquakes on housing prices in this study. Since this measure increases slowly over time and also takes positive values outside the area formally labeled as being subject to earthquakes, we are able to simulate the propagation of the impact of earthquakes on housing prices over time and across space.

There are three issues with this overall measure requiring further attention. First, if the argument of the natural log takes values on the interval  $(0, 1)$ ,  $e_i$  will be negative. In line with this, the interval on which total PGV takes values ranges from  $-3.95$  to  $+3.66$  in our sample. The purpose of this study is to find a threshold value below which this measure can be set to zero since it does not affect housing prices and above which this measure has an increasingly larger negative effect on housing prices. Since the latter effect is also not likely to be (log-)linear, it is better to split it up into different segments ( $e_{s_i}$ ) and then to determine the impact of each segment. A similar kind of approach is used by Cheung et al. (2018) based on the number of earthquakes in different categories of magnitude and Atlas voor Gemeenten (2017) based on the percentage of damages in different sub-areas recognized by the gas-extracting company NAM. In this study segments are used of 0.1.

A second issue is that total PGV appears to be trend-stationary, as illustrated in Figure 3.1. Although the earthquakes with a magnitude greater than 3 on the Richter scale in the Groningen gas field area shown in the right panel occur once or twice a year, the number of earthquakes greater than 1 in the left panel shows an upward trend, and so does total PGV. If regressed on a set of year dummies (21 in total), as well as municipality dummies (66 in total), the  $R$ -squared of this regression turns out to be 0.8687. This implies that year dummies, a set of variables that is commonly used in hedonic price regressions to control for business cycle effects (see Füss and Koller (2016), among others), and our PGV measure do not go together due to multicollinearity. If housing prices are taken to depend on both, the year dummies absorb part of the impact of the earthquakes and might lead to biased estimates. To prevent this we will control for business cycle effects by time-specific cross-sectional averages, an approach that will be explained in more detail in section 3.4.

A final issue is that especially the province of Drenthe has also been hit by earthquakes<sup>7</sup>, though not caused

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<sup>7</sup>Among which 3 earthquakes greater than 3 on the Richter scale in the municipality of Emmen (Roswinkel) during 1997-2000.

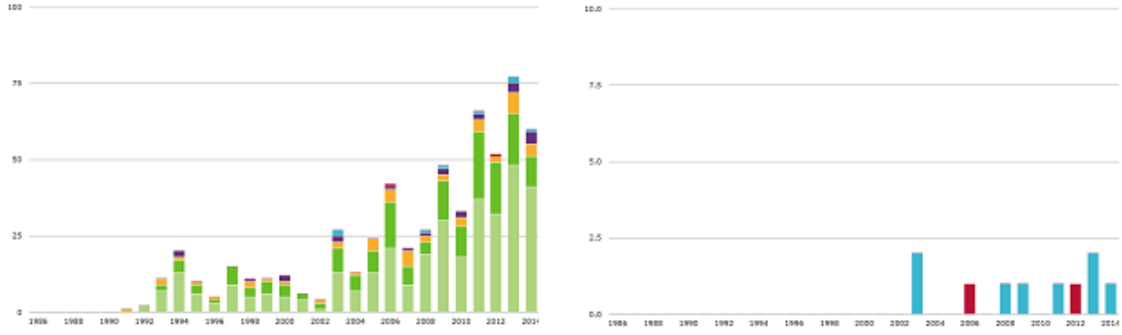


Figure 3.1: Number of earthquakes greater than 1 (left panel) and greater than 3 (right panel) on the Richter scale over the period 1986-2014 (Source: <https://www.nam.nl/feiten-en-cijfers/aardbevingen.html>).

by gas extraction from the Groningen gas field. When estimating the model these earthquakes have also been accounted for, but when determining the loss of value of houses prone to gas extraction from the Groningen gas field, they are not and be removed from the total PGV.

### 3.3. Spatio-temporal-similarity $W$ matrices

Realtors who are members of the NVM determine the asking price of a house by fitting a house-specific hedonic model using data on past transactions. Each transaction is weighted by its degree of similarity; nearer and more similar houses are given larger weights than distant and more different ones. Similarity between houses is assessed by computing an index that quantifies the "distance" for a set of characteristics. A detailed description of this methodology is given by Op't Veld et al. (2008). Based on this study we have developed a comparable similarity index.

Let  $N$  denote the number of houses in the sample, and  $S$  a symmetric  $N$  by  $N$  matrix whose elements  $s_{ij}$  measure the degree of similarity between each pair of houses. Following Op't Veld et al. (2008), three groups of housing characteristics are considered ranked according to their relevance in the determination of the market value of a house: (i) characteristics that are of primary importance since they cannot be changed, among which location, type of house, and lot size, (ii) characteristics that are of secondary importance since they can be changed, among which bathing facilities, state of maintenance, and the orientation of the main garden, and (iii) characteristics that are subjective like the kitchen (new, old, color, open, living-kitchen size). Let  $k_{xig}$  denote the standardized score of characteristic  $x_{ig}$  of house  $i$  within the group of characteristics  $g$ . Due to standardization, this score takes values on the interval  $[-1, +1]$ . The overall sub-score of house  $i$  within group  $g$  is obtained by summing over all the characteristics in that group, to get  $sc_{ig} = \sum_x k_{xig}$ , and by scaling the data using the resulting minimum and the maximum scores within the sample of  $N$  houses, yielding

$$sc_{ig} = \frac{\sum_x k_{xig} - sc_g^{min}}{sc_g^{max}}. \quad (3.3)$$

By averaging these sub-scores by their relevance, the  $\{i, j\}^{th}$  element of the matrix  $\mathbf{S}$ ,  $s_{ij}$ , representing the similarity of house  $i$  to house  $j$  is obtained by:

$$s_{ij} = \exp \left\{ - \left| \sum_{g=1}^3 r_g s_{c_{ig}} - \sum_{g=1}^3 r_g s_{c_{jg}} \right| \right\} \quad (3.4)$$

where  $r_g$  are weights given to each group, such that  $\sum_{g=1}^{g=3} r_g = 1$ .<sup>8</sup> If a house is fully similar,  $\exp(-0) = 1$ , while this value decreases exponentially to zero as the degree of similarity diminishes.

Let  $\mathbf{W}^*$  denote an  $N$  by  $N$  spatial weight matrix whose elements  $w_{ij}^*$  equal one if another house  $j$  has been sold in the neighborhood of house  $i$  before its asking price has been set, and zero otherwise. Then a spatio-temporal-similarity matrix is obtained by computing the Hadamard product of the two matrices  $\mathbf{W}^*$  and  $\mathbf{S}$ , yielding

$$\mathbf{W}^* \odot \mathbf{S} = \begin{pmatrix} 0 & 0 & \dots & 0 & 0 \\ w_{2,1}^* s_{2,1} & 0 & \dots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ w_{N-1,1}^* s_{N-1,1} & w_{N-1,2}^* s_{N-1,2} & \dots & 0 & 0 \\ w_{N,1}^* s_{N,1} & w_{N,2}^* s_{N,2} & \dots & w_{N,N-1}^* s_{N,N-1} & 0 \end{pmatrix}.$$

After this multiplication, the matrix is normalized such that the elements in each row sum up to one, to get  $\mathbf{W}$ . In the next section we will also introduce a spatial weight matrix during the period the house is on the market. As thresholds we use a distance of 10 kilometers from the focal house and a time period of six months prior to the date at which it was put for sale or when it was sold. This period of six months is in line with a recent study of Dubé et al. (2018). Importantly, if the data are ordered according to the date at which each house was sold, the corresponding matrix  $\mathbf{W}^*$  will be lower triangular. We will make use of this property when deriving the marginal effects of the explanatory variable in the model. Further note that the multiplication by the similarity index has the effect that the weights assigned to each of the houses increase with their degree of similarity and that those houses that are irrelevant, while selected, get a lower weight. In this respect the criteria to consider a distance of 10 kilometers and a predated period of 6 months rather than any other number have only a limited effect on the final estimation results.

### 3.4. Econometric specification

The hedonic equation adopted in this paper to determine the impact of earthquakes on housing prices can be characterized as a spatial Durbin model (SDM) with different spatial regimes, and controls for spatial fixed effects and common factors. It is based on the latest developments in econometrics in general and spatial econometrics in particular. Below the rationale behind these characteristics will be explained in more detail. The model takes the following form:

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<sup>8</sup>We used  $r_1 = 0.5$ ,  $r_2 = 0.3$ , and  $r_3 = 0.2$

$$p_i = \delta_a \sum_{j=1}^N w_{ij}^a p_j + \delta_t \sum_{j=1}^N w_{ij}^t p_j + \sum_{s=1}^S \lambda_s e_{s_i} + X_i \beta + \left( \sum_{j=1}^N w_{ij}^a X_{ij} \right) \theta + \gamma_{0m_i} + \gamma_{1m_i} \bar{p}_{t_i} + \epsilon_i \quad (3.5)$$

where  $p_i$  denotes the natural logarithm of the transaction price of house  $i$  per square meter of living space.<sup>9</sup> The variable  $e_{s_i}$  with coefficient  $\lambda_s$  represents one of the segments  $s$  in which total PGV is split up; it takes a value of one if total PGV takes a value within that segment, and zero otherwise. The row-vector  $X_i$  with coefficients  $\beta$  cover the characteristics of the house and of the neighborhood, summarized in Table A.1.

The model contains two spatial regimes in the spatially lagged dependent variable. These regimes capture the extent to which the price of a house is affected by the price of houses surrounding it, first before it was put for sale and then before it was sold but only during the time it was on the market.  $w_{ij}^a$  and  $w_{ij}^t$  are elements of the respective spatio-temporal-similarity matrices  $\mathbf{W}^a$  and  $\mathbf{W}^t$  and denote the weights given to houses within a distance of 10 kilometers of the focal house  $i$  that have been sold not earlier than 6 months prior to the date at which it was put for sale or when it was sold based on their similarity index.<sup>10</sup> Since these two sets of houses affect the price formation process of the focal house at different moments in time, one before and one after the asking price is set, their coefficients  $\delta_a$  and  $\delta_t$  are allowed to be different. The set of variables  $w_{ij}^a X_{ij}$  captures the extent to which the price of a house is affected by the explanatory variables of houses surrounding the focal house, i.e., their housing and neighborhood characteristics. Their impacts are measured by the coefficients  $\theta$ . A spatial econometric model that contains not only the variables  $X_i$  but also their spatial lags is known as a spatial Durbin model (Elhorst, 2014, p.9). These spatial lags, which are pre-multiplied by the spatio-temporal-similarity matrix  $\mathbf{W}^a$ , are known as spatial Durbin or SLX (spatial lag of X) terms.

The variables described so far are meant to cover potential spatial dependence (weak cross-sectional dependence) among the observations. The common factor meant to cover potential strong cross-sectional dependence is defined as the cross-sectional average of the dependent variable (the natural logarithm of the transaction price per square meter of living space) over our research area in each transaction year. This variable is denoted by  $\bar{p}_{t_i}$ , where the index  $t_i$  is used to indicate whether the transaction of house  $i$  takes place in year  $t$ . This variable enters the equation with unit-specific coefficients for each municipality  $\gamma_{1m_i}$ , where the index  $m_i$  is used to indicate whether house  $i$  is located in municipality  $m$  ( $m = 1, \dots, M$ ). The original idea to control for common factors in a non-spatial model goes back to Pesaran (2006). Bailey et al. (2016a) extend this idea to a spatial model, though by addressing strong and weak cross-sectional dependence in two separate stages, while Halleck-Vega and Elhorst (2016) and Shi and Lee (2017) demonstrate that both types of cross-sectional dependence are better accounted for simultaneously, the former when using cross-sectional averages and the latter when using principal components to approach common factors. Both studies also demonstrate that time-

<sup>9</sup>This variable is also used in Koster and Van Ommeren (2015), Bosker et al. (2016), and Atlas voor Gemeenten (2017).

<sup>10</sup>If the period it was on the market was shorter than six months, this period has been adjusted accordingly.



period fixed effects are a special case of common factors, as it requires the restriction  $\gamma_{11} = \dots = \gamma_{1N} = \gamma_1$ , i.e., the common factor with municipality-specific coefficients is replaced by a time dummy with a common coefficient  $\gamma_1$  for all municipalities. In contrast to these cited studies, this paper is among the first to apply this approach using micro rather than macro or aggregated data. The development of  $\bar{p}$  over time closely follows the business cycle. It reaches its peak in 2007, the year in which the global crisis started spreading, and before which all housing prices in the sample went up and after which they all fell up to and including 2013. In 2014 the housing market slightly recovered. The municipality-specific slope coefficients of this variable allow the impact of this crisis to differ from one municipality to the other, as some may have been hit harder than others. It should be stressed that the set of  $\gamma_1$  parameters also captures the impact of population growth or decline. Due to the move of younger people from the countryside to the urban areas, they allow the slope coefficients of rural municipalities to be lower than those of urban municipalities. Furthermore, it is to be noted that the impact of population growth or decline is also covered by a wide range of explanatory variables, among which the number of addresses per square km, distance to the nearest restaurant, supermarket, and train station, the type of neighborhood where it is located, the percentage of people aged between 15 and 24, 25 and 65, as well as over 65, a dummy variable measuring whether the population declined in the preceding period, and the percentages of people who are inactive on the labor market, who receive unemployment benefits, and who receive disability benefits. All these variables are measured at the neighborhood level.

The set of parameters  $\gamma_{0m_i}$  represent municipality fixed effects, while  $\epsilon_i$  denotes a disturbance term with zero mean and finite variance  $\sigma^2$ . Note that it should be avoided that the municipality fixed effects and the municipality-specific coefficients for the common factor absorb the impact of earthquakes. If this happens the coefficients of the earthquake variables may be biased downwards. This is avoided by considering a sample period that is sufficiently long, i.e., a period that also captures observations in which earthquakes had no impact. Some studies claim that the impact of earthquakes can only be effectively determined using data from 2012 onwards or did not have any (significant) effect before 2013 (Bosker et al., 2016), the year in which the Dutch government formally declared that gas extraction induced earthquakes (or before the Huizinge earthquake in August 2012). The basic idea is that people acting on the housing market were not aware of the risks before this declaration. However, it is questionable whether this is really the case. Research by De Kam and Raemaekers (2014) provides evidence that this awareness already existed in 2009. It indicates that searching buyers of a house already observed that the conditions of houses located in the earthquake area were deteriorating, although we do not know since when. Since we employ data from 1993 onwards, we may say that our data set covers a long time period in which the earthquakes had no impact at all. If they really started to have effect from 2012 onwards, then the period in which they had no effect covers 19 of the 22 years. It indicates that the municipality fixed effects and the municipality-specific coefficients of the common factor do not or hardly absorb any effect of the earthquakes.

The parameters of Equation (3.5) can be estimated by ordinary least squares (OLS).<sup>11</sup> Importantly, the right-hand side variables  $\sum_{j=1}^N w_{ij}^a p_j$  and  $\sum_{j=1}^N w_{ij}^t p_j$  may be treated as exogenous due to the lower triangular structure of the spatial weight matrices  $\mathbf{W}^a$  and  $\mathbf{W}^t$  (Pace et al., 1998). This structure is obtained by temporally ordering the observations by their transaction date and based on the property that houses that have been sold respectively before the asking price of the focal house has been set or before its transaction price has been determined may affect the transaction price of the focal house, but not vice versa. Similarly, the common factor may be treated as exogenous based on the assumption that the contribution of each single house to the cross-sectional average at a particular point in time goes to zero if the number of houses that is sold goes to infinity (Pesaran, 2006, assumption 5 and remark 3). Since the minimum number of houses that has been sold in a particular year amounts to 4228, this assumption may be said to be satisfied.

### 3.5. Direct and spillover effects

Direct interpretation of the coefficients in Equation (3.5) is difficult, because they do not represent the marginal effects of the explanatory variables. These effects can be obtained by taking partial derivatives of the reduced form of the model in vector notation. First, the model is rewritten in vector form

$$\mathbf{P} = \delta_a \mathbf{W}^a \mathbf{P} + \delta_t \mathbf{W}^t \mathbf{P} + \mathbf{E}_s \lambda + \mathbf{X} \beta + \mathbf{W}^a \mathbf{X} \theta + \mathbf{\Gamma}_0 + \mathbf{\Gamma}_1 \bar{\mathbf{P}} + \epsilon, \quad (3.6)$$

where all small letters in Equation (3.5) are changed into bold capitals and/or their index  $i$  has been removed to denote their vector or matrix counterparts. Moving the two right-hand side variables  $\mathbf{W}^a \mathbf{P}$  and  $\mathbf{W}^t \mathbf{P}$  to the left of Equation (3.6), and multiplying both sides by the spatial multiplier matrix  $(\mathbf{I} - \delta_a \mathbf{W}^a - \delta_t \mathbf{W}^t)^{-1}$ , yields the reduced form of the model. Generally, the determination of the marginal effects is hampered by the fact that it is not possible to present an analytical solution for the inverse of the spatial multiplier matrix. However, since the spatial weight matrices are lower triangular, we have  $(\mathbf{I} - \delta_a \mathbf{W}^a - \delta_t \mathbf{W}^t)^{-1} \approx \mathbf{I} + \delta_a \mathbf{W}^a + \delta_t \mathbf{W}^t$  (Bhattacharjee et al., 2016).<sup>12</sup> Consequently, the partial derivatives of the expectation of the dependent variable,  $E(\mathbf{P})$ , with respect to one particular PGV segment  $\mathbf{E}_s$  ( $s = 1, \dots, S$ ) representing the impact of earthquakes can be seen to take the form<sup>13</sup>

$$\left( \frac{\partial E(\mathbf{P})}{\partial \mathbf{E}_s} \right) = (\mathbf{I} + \delta_a \mathbf{W}^a + \delta_t \mathbf{W}^t) \lambda_s. \quad (3.7)$$

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<sup>11</sup>Alternatively, they can be estimated by the least squares dummy variables (LSDV) estimator set out in Baltagi (2008). This estimator first eliminates the municipality dummies from the equation by demeaning the dependent variable and the explanatory variables, and then estimates the equation using the demeaned variables by OLS.

<sup>12</sup>Higher-order terms are negligible if the  $\delta$ -parameters are relatively small and/or if the elements of  $\mathbf{W}$  are small. This effect is strengthened by the property that  $\mathbf{W}$  is lower triangular.

<sup>13</sup>Note that municipality dummies and common factors, as well as the error term, drop out due to taking the expectation of the dependent variable.

The diagonal elements of this  $N$  by  $N$  matrix of marginal effects represent direct effects of total PGV on the price of the own house and its off-diagonal elements the indirect or spillover effects of total PGV on the price of other houses. Generally, these two types of effects are summarized by one summary indicator for the direct effect and one indicator for the spillover effect over all units in the sample; the former by the average diagonal element, and the latter by the average row sum of the off-diagonal elements of the  $N$  by  $N$  matrix of marginal effects (LeSage and Pace, 2009, Section 2.7). However, the purpose of this study is to determine the impact of earthquakes at the observational level of each individual house. Since each house at the moment it is sold is characterized by only one non-zero  $\lambda_s$ -value at most, the total effect will be 0 when total PGV is below the threshold value at which it does affect housing prices and  $\exp[(1 + \delta_a + \delta_t)\lambda_s] - 1$  when it is above it. Note that the use of the exponential function minus 1 provides a more accurate estimate of the marginal effect of a dummy than  $(1 + \delta_a + \delta_t)\lambda_s$  since the dependent variable is expressed in its natural log. Also note that the spatial weight matrices drop out from this expression since they are row-normalized.

The total effect can be subdivided into two different sub-effects: the direct effect of earthquakes on housing prices represented by  $\lambda_s$  and the spillover effect represented by  $(\delta_a + \delta_t)\lambda_s$ . This spillover effect measures the extent to which the price of the focal house is dependent on the price of its comparison set. It concerns houses surrounding the focal house which have similar characteristics, have been sold within a distance of 10 kilometer in the preceding six months, and which can be observed by both the house owner and searching buyers.

#### 4. Results

We first test for cross-sectional dependence using the CD test and the exponent  $\alpha$ -estimator adjusted as in Elhorst and Durán (2017) for unbalanced micro data sets based on the delineation of the research area into 66 municipalities and the research period into 21 years. The CD-test statistic amounts to 117.117 with an average pairwise correlation coefficient of 0.152. Since this statistic follows a standard normal distribution with critical values of -1.96 and 1.96 at the 5%-level, this outcome is highly statistically significant, indicating that strong cross-sectional dependence needs to be accounted for. The exponent  $\alpha$  amounts to 0.961 and is so close to the upper bound of 1 that it points to the existence of the strongest form of cross-sectional dependence of no distance decay effect at all, better known as common factors. When adding municipality fixed effects,  $\gamma_{0m_i}$ , and cross-sectional price averages to the model with municipality-specific coefficients,  $\gamma_{1m_i}\bar{p}_{t_i}$ , for  $i = 1, \dots, M$ , the estimate of  $\alpha$  reduces to 0.845, and when all variables are included (cf. Equation 3.5) to 0.570. These estimates demonstrate that both strong and weak distance decay effects over space can only be effectively factored out<sup>14</sup> when accounting for both common factors and spatial dependence (spatial Durbin terms) simultaneously.

The R-squared of the model amounts to 0.8288, which is high for a model based on so many observations.

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<sup>14</sup>This requires estimates of  $\alpha$  close to 0.5.

One explanation is that this model contains 81 housing and neighborhood attributes.<sup>15</sup> The coefficients of the two spatial regimes capturing the extent to which the price of a house is affected by the price of houses surrounding it are respectively positive and highly significant and negative and highly insignificant; the first regime with coefficient 0.5708 (t-value 91.71) measures the impact of similar nearby and previously sold houses before the asking price is set, and the second regime with coefficient -0.0001 (t-value -0.33) before the house is sold at its transaction price. The coefficient of this second regime is so small that it might be ignored. In addition to the housing and neighborhood attributes, the hedonic price model also contains their spatial lags (except for the three variables measuring the percentage of people in different age categories at the neighborhood level and the dummy whether its population declined, see appendix). Many studies ignore these so-called spatial Durbin terms, probably based on the expectation that they, just as the second spatial price regime variable, are of minor importance. However, the opposite is true; no less than 65 of these 77 terms are statistically significant at the 5% level. They reflect the micro approach used by realtors to assist their clients. Importantly, neither of the studies published in Dutch cited earlier account for these spatial Durbin terms. This raises the question whether they are capable to answer the policy question to which extent earthquakes contributed to market value depreciation in the affected area (Francke and Lee, 2013; Bosker et al., 2016; Atlas voor Gemeenten, 2017; CBS, 2017). To further illustrate the importance of the spatial Durbin terms, we decompose the R-squared value using the Shapley-based method set out in Israeli (2007) for five sets of variables: the housing and neighborhood characteristics of the house itself, their spatial Durbin counterparts, the municipality dummies, the cross-sectional averages of housing prices with municipality-specific parameters, and the PGV segment variables. The absolute contribution  $C_S^A$  of each set  $S$  is calculated as

$$C_S^A = 0.5 * (R_F^2 - R_{F-S}^2) + 0.5 * (R_S^2 - R_0^2), \quad (4.1)$$

where  $F$  represents the full model,  $F - S$  the full model excluding the set  $S$ , and 0 the model only including the intercept. By dividing these absolute contributions by their sum, we obtain the relative contribution of each set of variables to the R-squared value. The results point out that with 70.56% the housing and neighborhood characteristics of the house itself contribute most to the explained variation in housing prices, followed by the spatial Durbin terms which are responsible for 11.89% of the variation. The common factors representing business cycle effects account for 11.67%, the municipality dummies for 5.65%, and finally the PGV segment variables for 0.23% of the variation. The relatively low contribution of the last set of variables indicates that the number of houses that is affected by earthquakes is small relative to the total number of observations in the sample. However, this set appears to have a major impact on housing prices that are affected.

A crucial component of the market value depreciation of affected houses is the sum of the direct and spillover

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<sup>15</sup>Some housing characteristics are split in many sub-categories with respect to a particular reference situation, among which period of construction (8), type of house (8), garage (5), isolation (4), heating (3), living room (5), and fireplace if present (2), location of the garden (8), the outside maintenance of the house (8), the type of road to which it is located (2), and the type of neighborhood (3).

effects related to different PGV segments using Equation (3.7). The results obtained for 2014, the last year of our sample period, are recorded in Table 4.1. The first column reports the successive PGV segments. For houses in the segment 1.3-1.4 or lower, we find no significant negative direct effect. For this reason, these segments may be said to represent the endogenously determined control group or the threshold below which earthquakes have no effect on housing prices. Interestingly, all municipalities located in the province of Friesland, located west of the province of Groningen, are part of this control group. The same applies to municipalities in the southern part of the province of Drenthe, located south of the province of Groningen. By contrast, almost all municipalities located in the province of Groningen itself<sup>16</sup>, as well as some municipalities located in the northern part of the province of Drenthe are part of the area in 2014 that according to our model outcomes turn out to be affected by earthquakes. Importantly, this area is much wider than the eight municipalities that have formally been declared to belong to the risk area in 2013 and that have subsequently been taken as point of departure in the first wave of policy studies, as well as the extension of this area to respectively 9 and 11 municipalities later. It is also in line with the number of physical damages due to earthquakes that have been reported in different municipalities. These data have been made available by the province of Groningen. This area also covers almost all municipalities in the province of Groningen and some in the province of Drenthe.<sup>17</sup>

The first segment experiencing a direct negative effect is 1.4-1.5; the t-value of 2.02 (fourth column) indicates that houses in this segment do experience a significant price reduction of 1.18% (third column). The other results reported in third column show an upward trend to 27.26% in the highest segment. When inverting the relationship that has been used to determine total PGV, it follows that the first segment of 1.4 – 1.5 represents a total shaking of 4.3 cm/s, and the highest segment starting at 3.2 of 24.6 cm/s. Recall that this cumulative measure is not due to one but a series of earthquakes. Postmes and Stroebe (2017) show that especially the recurring experience of earthquakes and uncertainty about how many earthquakes will still follow may strengthen the observed negative effects. Furthermore, in a meta-analysis of 20 studies, Koopmans and Rougoor (2017) corroborate the view that the perceived risk of earthquakes declines if no new earthquakes occur, but remain or are even strengthened when new ones present themselves all the time. One reason why the reported loss of values do not show a fully smooth upward trend might be due to measurement errors in the total PGV measure. Equation 3.1 is not a physical law, but a regression equation that has been estimated and that is subject to statistical noise. The accumulation of this statistical noise over a series of earthquakes may cause some unevenness.

Using the numbers reported in Table 4.1, the loss of value of each individual house located in the risk area ( $PGV > 1.4$ ) in 2014 can be simulated. It concerns 2.640 houses. Figure 4.1 graphs the loss of value of these

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<sup>16</sup>Except for the municipalities of Bellingwedde, Vlagtwedde, and Stadskanaal at the east-side of the province of Groningen, and Grootegast and Marum at the west-side.

<sup>17</sup>It concerns the municipalities of Leek, Noordenveld, Tynaarlo, and Aa and Hunze. Generally, if the number of reported physical damages is high, then also either the number of sold houses affected by earthquakes in 2014 is high, the price devaluation, or both. Examples are Loppersum (3305 damages, 46 sold houses in 2014, price fall 22.23%), Veendam (335, 122, 5.01%), and Leek (25, 7, 1.99%).

Table 4.1: Price devaluations per PGV segment in 2014

| PGV segment | # Houses | Price fall (%) | T-value |
|-------------|----------|----------------|---------|
| 1.4 – 1.5   | 173      | 1.18           | 2.02    |
| 1.5 – 1.6   | 171      | 2.60           | 3.40    |
| 1.6 – 1.7   | 238      | 4.77           | 5.66    |
| 1.7 – 1.8   | 227      | 5.18           | 6.21    |
| 1.8 – 1.9   | 190      | 5.64           | 6.69    |
| 1.9 – 2.0   | 264      | 8.22           | 9.39    |
| 2.0 – 2.1   | 268      | 10.62          | 11.93   |
| 2.1 – 2.2   | 233      | 12.25          | 13.48   |
| 2.2 – 2.3   | 202      | 9.75           | 11.12   |
| 2.3 – 2.4   | 175      | 11.40          | 12.94   |
| 2.4 – 2.5   | 140      | 14.87          | 16.86   |
| 2.5 – 2.6   | 98       | 18.22          | 19.84   |
| 2.6 – 2.7   | 72       | 16.26          | 18.58   |
| 2.7 – 2.8   | 43       | 16.20          | 19.08   |
| 2.8 – 2.9   | 55       | 17.18          | 20.65   |
| 2.9 – 3.0   | 31       | 20.42          | 23.78   |
| 3.0 – 3.1   | 20       | 20.82          | 25.10   |
| 3.1 – 3.2   | 21       | 22.47          | 27.72   |
| > 3.2       | 19       | 27.26          | 31.55   |

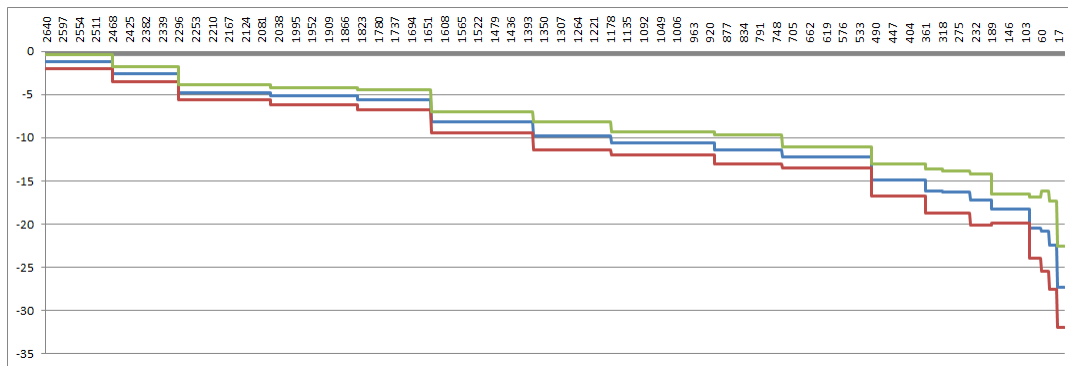


Figure 4.1: The blue line reflects housing market depreciation in percentage points and number of houses being affected in 2014. The red line reflects the lower bound and the green line the upper bound of the confidence interval.

houses in ascending order, as well as the corresponding confidence interval. This interval is obtained by drawing the parameter estimates that are needed to calculate the direct and spillover effects implied by Equation 3.7 100 times from the estimated variance-covariance matrix of the corresponding parameters. The confidence interval shows that the statistical accuracy with which the losses of value can be calculated is relatively small.

Based on the numbers underlying this graph, also the average loss of value in 2014 of houses prone to earthquakes can be calculated, which turns out to be 9.3%. When repeating the whole analysis for 2013<sup>18</sup>, a price fall of 7.2% regarding 1.817 housing transactions is obtained. Continuing in this fashion, we find a loss of value of 5.2% for 1.627 houses in 2012, of 3.2% for 1.122 houses in 2011, 4.5% for 503 houses in 2010, and 3.0% for 321 houses in 2009. The threshold value above which earthquakes appear to have any effect is identified to be also 1.4 in 2013, but to be higher in the preceding years: 1.7 in 2012, and 1.9/2.0 over the period 2009-2011. When using data up to 2008 no clear threshold value can be determined any more. These numbers show that the earthquakes started to have a price-reducing effect in 2009, which is in line with research of De Kam and Raemaekers (2014). Apparently, houses for which the cumulative PGV measure exceeded the lower bound of 1.7 – 2.0 were judged by searching buyers as having a disamenity for which they wanted to be financially compensated by, on average, 3.0% in 2009 up to 5.2% in 2012. After 2012, when the attention for earthquakes substantially increased, both by the Dutch government and the media, this financial compensation almost doubled within two years. Worrying is not only the magnitude of this loss of value but also the increasing number of affected houses, partly because the threshold below which earthquakes affect housing prices felt down to 1.4 in 2013 and 2014. The earthquake problem in the province of Groningen can perhaps be best characterized as a permanent shock that is constantly increasing in size; the risk area becomes broader and wider over time and once located in the risk area the extent to which housing prices are under pressure becomes bigger and stronger.

Our average price reduction in the range of 7.2-9.3% after 2012 is greater than that which has been found in previous studies. By recalling the methodological breakthroughs of this study compared to these previous studies, we are able to understand why. Over the period 2012Q3-2016Q4, CBS (2017) finds a non-significant price differential of 1.9% between houses in the highest risk segments and those in their reference area. However, their reference area contains many municipalities and neighborhoods within the province of Groningen, which according to the results of our study are also affected by earthquakes. This objection of a too small risk area also plagues the study of Francke and Lee (2013). They find that housing prices in their reference area increased less than in the risk area over the period 1993Q1-2013Q1, decreased more over the period 2009Q1-2013Q1, the period in which housing prices started to decline due to the global crisis, and also decreased more over the period 2012Q4-2013Q1, the period after which the heaviest earthquake took place up to now. The main problem with the studies of Francke and Lee (2013) and CBS (2017) is that they do not employ any earthquake measure but compare the development of housing prices in an area that is labeled as being subject to earthquakes in advance, and a selection of reference areas which are assumed not to be affected by earthquakes with (almost) similar background statistics. By not making the determination of the risk area part of their research, which in addition

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<sup>18</sup>Estimating the model using data up to and including 2013, determining the threshold value below which earthquakes have no effect, and simulating the loss of value of houses that are affected.

might change over time, they assign houses to reference areas while they are actually at risk.

The problem of using a pre-defined risk area also applies to Bosker et al. (2016); they only consider houses that have been sold in the eight municipalities belonging to the area formally declared as being at risk. They compare the price development of these houses with reference houses which, just as the houses in the province of Groningen, are located in the periphery of the Netherlands. It concerns not only locations centered around their relatively small risk area, among which some locations in the province of Groningen, but also in Groningen's two neighboring provinces Friesland and Drenthe, as well as locations in other provinces along the east border of the country, the provinces of Zeeland and Limburg in the south of the Netherlands, and the upper part of North-Holland. By doing so the authors are, just as this study, able to control for business cycle effects and population decline. They find no price differential until 2012Q3, but of 2.2% after it (until 2015Q3). However, when treating the whole province of Groningen as risk area, as a robustness check in appendix 3 of their report, they find a loss of value ranging from 5.2 to 6.5%, depending on the model variant being considered. The latter values are much closer to the outcomes of this study. Furthermore, De Kam (2016) demonstrates by means of robustness checks that these percentages reported in Bosker et al. (2016) become even higher when changing some of their assumptions. It corroborates the view that the determination of the risk area should be part of the analysis and cannot be determined in advance.

Another and related issue is that they also do not determine the moment at which earthquakes started to have effect. They mainly focus on price effects after the Huizinge earthquake of 3.6 on August 16, 2012. To investigate whether there have been price effects before Huizinge, they limit themselves to the period Januari 1, 2011 to August 15, 2012. Although they do find a price effect which in one model variant increases up to 1.8%, they shift this result aside based on the argument that it is statistically insignificant. However, they do not realize that this might have been caused by the limited number of observations (< 4000) on which their analysis is based. In their follow-up study (Atlas voor Gemeenten, 2017), they investigate which area is at risk. Using the percentage of damages recognized by the NAM (note: the gas-extracting company which is responsible), the authors find that this area is larger than the eight municipalities in their previous study. However, they do not investigate whether this also has consequences for the period before Huizinge. To some extent they are also unable to do so since the reporting of damages started after the formal declaration by the Dutch government in 2012 that some municipalities are at risk. As said, Atlas voor Gemeenten (2017) finds that the average price reduction after Huizinge (until June 2017) amounts to 2.2%. This does not seem like much, but according to our study we also find a price reduction that amounts to 2.0 to 4.1% after Huizinge. The issue is that there has also been a price reduction of 3.0-5.2% before Huizinge. The explanation is that houses in the lower PGV segments before Huizinge have moved upwards to higher segments after Huizinge due to new earthquakes that occurred, while new houses entered the lower segments.

Koster and Van Ommeren (2015) find that every earthquake that can be felt at the location of the house before it was sold ( $> 0.5$  cm/s) causes a price reduction of 1.9%. They find no effect of weaker earthquakes,



but the problem might be that time dummies, which they also include, absorb the impact of earthquakes since their earthquake measure tends to be trend-stationary. This is the reason why we use cross-sectional averages rather than time dummies. Cheung et al. (2018) investigate the impact of induced earthquakes on residential property values using sales data from Oklahoma over the period 2006-2014 and find that at least one earthquake of magnitude 3-4 already causes a price reduction of 3.5% when using a repeated sales approach and of 4.5% when using a difference-in-difference approach, where the year 2010 when earthquakes according to the authors started to occur is used as a time point to split the sample in a risk and a reference area. Importantly, neither of the above studies, including the last two, account for spatial dependence, while this is a widely accepted approach in both the real estate and spatial econometric literature, and we have found ample evidence that spatial dependence representing the sales comparison approach needs to be accounted for. We demonstrated this by counting the number of spatial Durbin terms that turn out to be significant (65 out of 77) and by determining their contribution to the R-squared (11.89%).

## 5. Compensation scheme

In this study we determined the loss of value of houses that have been sold. An important policy question is whether this loss of value can also be simulated for houses that have not been sold. Using our model as point of departure, we appoint different options for the type of information needed to develop such a compensation scheme. Probably the most extensive option is the following. First, the coordinates of the house (longitude and latitude) are needed, so as to be able to determine the extent to which it has been hit by earthquakes before a particular reference date and, related to that, the corresponding loss of value in percentage points. Next, the characteristics of the house and the neighborhood are needed at the reference date, so as to be able to determine the price of the house using Equation (3.5) and, subsequently, to translate the loss of value from percentage points into euros. Finally, a reference date is needed at which the house has been sold fictitiously. This is difficult since the loss of value and the number of houses being affected increased over time, at least until 2014. At the same time, it is to be expected that this financial loss will stabilize itself and may even decrease after 2014 because the Dutch government and the gas extracting company NAM have taken several policy measures in and around 2014 to get the problem under control. One such measure is that gas extraction has been gradually decreased from 2014 onwards, while there are plans, unfold in 2018, to quit gas extraction in 2030 completely. This implies that (the probability of) earthquakes will slowly die out and that the housing price shock might come to an end in the (very) long term. This is illustrated in Figure 4, where  $t_0$  represents the time point at which earthquakes started to have an effect on housing prices,  $t_2$  the time point at which the earthquake problem is expected to come to an end, and  $t_1$  reflects the turning point at which the price fall starts to diminish due to measures to get the earthquake problem under control. The upper line depicts the price of houses not affected by earthquakes. This curve is U-shaped since prices started to decline after 2007 due to the global

## Housing price

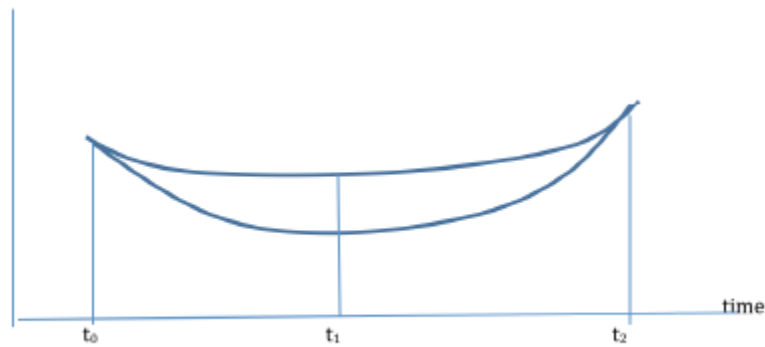


Figure 4: Welfare loss: the bottom line reflects the price development of houses affected by earthquakes, and the upper line of those that are not

financial crisis and started to recover in 2014. Similarly, the bottom line depicts the price of houses affected by earthquakes.

If a searching buyer purchased a house in the risk area at a particular point in time, all future welfare losses up to the point at which the housing price shock is expected to come to an end ( $t_2$ ) are discounted in the price he is willing to pay for that house, as a result of which the financial compensation for the seller of the house at that particular point in time can be determined. For example, if the buyer purchased the house at  $t_1$ , the distance from the bottom to the upper line at  $t_1$  reflects all future welfare losses. If a house has been put for sale but has not been sold yet, the date at which it has been put for sale can be used as a reference date. However, if a house has also not been put for sale, it is not immediately clear which point in time should actually be used, while the closer (the further away) it will be to the turning point  $t_1$ , the higher (lower) the financial compensation according to this scheme would be. At the same time, a house owner also needs to be compensated for all the troubles he has encountered, i.e., the period he has experienced a potential loss of value and the extent to which this has impeded him to sell his house. Theoretically, if somebody sells his house at  $t_2$ , the welfare loss would be 0, even though this house owner has gone through a difficult time during the period  $t_2 - t_0$ .

Recently, Atlas voor Gemeenten (2017) has found that the loss of value caused by earthquakes has reached its turning point due to the announcement of compensating measures in January 2014. On April 29, 2014 the NAM formally started compensating market value depreciation. If instead of the date house owners sold their house or have put it for sale this date set by the NAM is chosen as reference date, it prevents the objection that house owners who did not put their house for sale yet get less compensation. Furthermore, payments for housing depreciation already made to house owners can be set off against the compensation still to be determined, while payments made after the reference date or payments that still have to be made can be increased by the statutory interest rate.

One potential objection against the outlined compensation scheme may be its implementation costs. There are indications that the valuation costs and costs of registering housing characteristics, including appeals against

the outcomes, exceed the price fall of houses in areas prone to earthquakes. A much cheaper option in this respect is to take the so-called WOZ-value determined by the Dutch Real Estate Appraisal Act on an annual basis. If April 29, 2014 is used as reference date and the WOZ-value on January 1, 2014 (or 2013 or 2012), then the only information needed are the coordinates of the house (longitude and latitude). When this scheme is chosen a one-off compensation for all house owners in the affected area without significant implementation costs can be realized.

It should be stressed that this is also the reason why we eventually did not include spatial Durbin terms of the PGV segment variables in Equation (3.5). Just as the characteristics of other houses and neighborhoods surrounding the focal house may affect its price, so may the extent to which earthquakes hit other houses surrounding the focal house. Along this way, we could further differentiate the extent to which housing prices have fallen due to earthquakes in each PGV segment across the risk area. This happens if the focal house and its comparison set are in different PGV segments. We have re-estimated the model in Equation 3.5 with this extension<sup>19</sup> to see whether it was useful, but decided to disregard it for statistical reasons, and for its implementation costs and complexity. One statistical reason is that the correlation coefficient between the total PGV measure of the focal house and that of its comparison set appeared to be high: 0.98. This outcome implies that if the focal house is in PGV segment  $s$ , its comparison set is often also in PGV segment  $s$ , or in segment  $s - 1$  or  $s + 1$ .<sup>20</sup> The benefit of also considering PGV segment variables of the comparison set is therefore limited. Another statistical reason is that the coefficients of the PGV segment variables, both of the focal house and its comparison set, become more difficult to interpret and their significance levels would drop (partly due to multicollinearity), as a result of which the confidence interval of the price fall, graphed in Figure 4.1, would widen, which is not desirable.

The second reason not to include spatial Durbin terms of the PGV segment variables is that housing and neighborhood characteristics of the focal house then need to be collected again, causing high implementation costs. These characteristics are needed to be able to construct the similarity index set out in Equation 3.3 with all other houses located within a distance of 10 kilometers that have been sold in the six months preceding the reference date and, related to that, to determine the impact (the coefficient  $\tau_s$  mentioned in the last footnote) on the price of the focal house of the PGV segment to which its comparison set belongs. This would complicate the compensation scheme considerably.

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<sup>19</sup>A set of variables  $w_{ij}^a e_{s_j}$  with coefficients  $\tau_s$ , which just as total PGV, is split up into different segments of 0.1.

<sup>20</sup>For the same reason also the three variables measuring the percentage of people in different age categories at the neighborhood level and whether its population declined have been left aside.

## 6. Conclusion and discussion

We have developed a hedonic price model based on the latest developments in econometrics in general and spatial econometric in particular combining the micro approach used by realtors to assist their clients with the macro approach used in so many non-spatial studies to study the effect of housing characteristics and neighborhood (dis)amenities. The model is used to determine the impact of many small induced earthquakes due to gas extraction on housing prices in the three northern provinces of the Netherlands, using data on more than 220,000 housing transactions over the period 1994–2014. We have also sketched a scheme that can be used to compensate house owners for the loss of value they have experienced based on this model, and pointed out that its implementation costs can be kept to a minimum.

Before such a scheme is implemented there are a few model components that may be refined. First, the seismological model that is used to determine the extent to which houses have been prone to earthquakes has recently been improved. Updates have been made available by Bommer et al. (2017), while Kruiver et al. (2017) have found that the composition of the soil also has an impact on the ground motion caused by earthquakes. One reason why the reported loss of values in Table 4.1 do not show a fully smooth upward sloping pattern might be due to measurement errors in the total PGV measure. Maybe these newly developed formulas can take away some of the unevenness.

Second, data observed after 2014 may be used to investigate whether the loss of value indeed reached a turning point after which it started to decrease in response to several (policy) measures taken by both the Dutch government and the gas extracting company (NAM). One complication is that this also requires data of the NAM for each individual house owner who received financial compensation for market value depreciation, as well as recognized physical damages<sup>21</sup>, since this depreciation might be different from that of house owners who did not receive any financial compensation. Without these data the behavior of buyers and sellers acting on the Groningen housing market cannot be adequately modeled after 2014, since they may have discounted these measures in their behavior from that moment on. These data can also be used to better investigate whether there is any relation between the market value depreciation of houses and physical damages. Unfortunately, the NAM has not been willing to make these data available for independent scientific research yet.

Third, the municipality of Groningen may be treated as a dominant rather than a regular unit, thereby, following research of Holly et al. (2011) for the city of London and Van Nes (2018) for municipalities in the province of Drenthe.

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<sup>21</sup>It concerns the number of reported damages, the damages that have been recognized, the amount of money they received for each recognized damage and the point in time at which this compensation has been promised or paid.

## Appendix A.

Table A.1: Variable descriptions, mean values, and parameters estimates of model 3.5

| Variable                          | Mean    | Coeff. Var | T-value | Coeff. W*Var* | T-value |
|-----------------------------------|---------|------------|---------|---------------|---------|
| PGV 1.4 – 1.5                     | 0.0244  | -0.0076    | -2.80   |               |         |
| PGV 1.5 – 1.6                     | 0.0218  | -0.0168    | -5.80   |               |         |
| PGV 1.6 – 1.7                     | 0.0187  | -0.0311    | -9.85   |               |         |
| PGV 1.7 – 1.8                     | 0.0164  | -0.0338    | -9.94   |               |         |
| PGV 1.8 – 1.9                     | 0.0141  | -0.0369    | -10.04  |               |         |
| PGV 1.9 – 2.0                     | 0.0112  | -0.0546    | -13.18  |               |         |
| PGV 2.0 – 2.1                     | 0.0099  | -0.0715    | -16.14  |               |         |
| PGV 2.1 – 2.2                     | 0.0083  | -0.0832    | -17.33  |               |         |
| PGV 2.2 – 2.3                     | 0.0072  | -0.0653    | -12.60  |               |         |
| PGV 2.3 – 2.4                     | 0.0053  | -0.0770    | -12.99  |               |         |
| PGV 2.4 – 2.5                     | 0.0043  | -0.1025    | -15.75  |               |         |
| PGV 2.5 – 2.6                     | 0.0035  | -0.1281    | -17.75  |               |         |
| PGV 2.6 – 2.7                     | 0.0024  | -0.1129    | -13.25  |               |         |
| PGV 2.7 – 2.8                     | 0.0016  | -0.1125    | -10.86  |               |         |
| PGV 2.8 – 2.9                     | 0.0012  | -0.1200    | -10.12  |               |         |
| PGV 2.9 – 3.0                     | 0.0010  | -0.1454    | -10.94  |               |         |
| PGV 3.0 – 3.1                     | 0.0006  | -0.1486    | -8.80   |               |         |
| PGV 3.1 – 3.2                     | 0.0004  | -0.1621    | -7.84   |               |         |
| PGV > 3.2                         | 0.0004  | -0.2026    | -10.31  |               |         |
| Number of floors                  | 2.5543  | 0.0213     | 22.39   | -0.0349       | -5.71   |
| Living space (ln, $m^2$ )         | 4.7805  | 0.4936     | 237.44  | -0.0008       | -7.45   |
| Lot size (ln, $m^2$ )             | 5.7301  | 0.1290     | 165.40  | -0.0001       | -14.69  |
| Number of addresses per square km | 6.2809  | 0.0382     | 54.41   | -0.0001       | -18.81  |
| Distance to nearest restaurant    | 1.1186  | -0.0124    | -22.50  | 0.0193        | 7.31    |
| Distance to nearest supermarket   | 1.1396  | 0.0020     | 3.71    | -0.0080       | -3.30   |
| Distance to nearest train station | 6.8008  | -0.0081    | -38.48  | 0.0053        | 16.73   |
| Number of rooms                   | 4.6665  | 0.0153     | 33.81   | -0.0995       | -34.83  |
| Number of balconies               | 0.0773  | 0.0507     | 33.37   | 0.0269        | 2.25    |
| Surface area garden ( $m^2$ )     | 93.7357 | 0.0000     | 6.33    | 0.0001        | 3.58    |
| Built 1500-1905                   | 0.0497  | 0.0652     | 7.66    | -0.0362       | -0.98   |
| Built 1906-1930                   | 0.1214  | 0.0308     | 3.67    | -0.0296       | -0.82   |
| Built 1931-1944                   | 0.0815  | 0.0444     | 5.26    | -0.0128       | -0.35   |
| Built 1945-1959                   | 0.0605  | 0.0369     | 4.35    | -0.1879       | -5.11   |
| Built 1960-1970                   | 0.1478  | 0.0138     | 1.65    | -0.1528       | -4.25   |
| Built 1971-1980                   | 0.2298  | 0.0393     | 4.72    | -0.0506       | -1.44   |
| Built 1981-1990                   | 0.1386  | 0.0677     | 8.10    | -0.0234       | -0.65   |
| Built 1991-2000                   | 0.1349  | 0.1373     | 16.33   | 0.0037        | 0.10    |
| Built after 2000                  | 0.0334  | 0.1567     | 18.05   | -0.2805       | -7.25   |

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Table A.1 – Continued from previous page

| Variable  | Mean   | Coeff. Var | T-value | Coeff. W*Var* | T-value |
|---|--------|------------|---------|---------------|---------|
| Garage attached stone                                   | 0.2509 | 0.0823     | 66.85   | -0.0994       | -11.72  |
| Garage detached stone                                   | 0.1261 | 0.0736     | 53.13   | -0.1236       | -13.25  |
| Garage attached wood                                    | 0.0093 | 0.0499     | 12.13   | 0.0562        | 1.97    |
| Garage standing timber                                  | 0.0627 | 0.0549     | 30.53   | -0.1828       | -15.40  |
| Garage inside the house                                 | 0.0425 | 0.0971     | 46.01   | -0.1720       | -10.93  |
| Ground leased   | 0.0082 | -0.0895    | -20.40  | 0.2081        | 8.14    |
| Furnished   | 0.0066 | -0.2692    | -49.47  | -0.0663       | -3.97   |
| Type: Row house   | 0.2483 | -0.1952    | -5.29   | -4.6693       | -57.96  |
| Type: Terraced house                                    | 0.0269 | -0.1078    | -2.92   | -4.7202       | -57.13  |
| Type: Corner house                                      | 0.1417 | -0.1757    | -4.76   | -4.7494       | -58.92  |
| Type: Semi-detached                                     | 0.2528 | -0.1038    | -2.81   | -4.7815       | -59.02  |
| Type: Detached  | 0.3177 | 0.0352     | 0.95    | -4.8345       | -59.49  |
| Type: Apartment (before 1945)                           | 0.0053 | -0.2120    | -5.68   | -5.0829       | -59.75  |
| Type: Apartment (1945-1970)                             | 0.0036 | -0.3381    | -9.01   | -4.4385       | -44.86  |
| Type: Apartment (after 1970)                            | 0.0035 | -0.2359    | -6.25   | -4.5247       | -44.65  |
| Lift  | 0.0022 | 0.1087     | 11.25   | 0.0262        | 0.34    |
| Standard vs. located to quiet road                      | 0.5353 | -0.0044    | -4.80   | -0.0631       | -11.11  |
| Located to busy road                                    | 0.0330 | -0.0323    | -14.06  | 0.1993        | 11.77   |
| Standard vs. located outside built-up area              | 0.3893 | -0.0700    | -25.78  | -0.0913       | -5.58   |
| Located in residential area                             | 0.5106 | -0.0822    | -29.00  | 0.0360        | 2.13    |
| Located in center                                       | 0.0739 | -0.0593    | -19.18  | -0.0209       | -1.09   |
| Outside maintenance: Moderate to poor                   | 0.0008 | -0.0052    | -0.34   | -0.6391       | -6.82   |
| Outside maintenance: Moderate                           | 0.0122 | 0.0915     | 11.48   | -0.6564       | -13.65  |
| Outside maintenance: Moderate to reasonable             | 0.0033 | 0.1096     | 11.09   | -1.0617       | -16.14  |
| Outside maintenance: Pretty                             | 0.0738 | 0.2027     | 27.63   | -0.6534       | -15.31  |
| Outside maintenance: Fair to good                       | 0.0349 | 0.2327     | 30.94   | -0.7121       | -16.03  |
| Outside maintenance: Good                               | 0.7666 | 0.3207     | 44.17   | -0.6369       | -15.08  |
| Outside maintenance: Good to excellent                  | 0.0108 | 0.3785     | 46.26   | -0.8679       | -16.57  |
| Outside maintenance: Outstanding                        | 0.0947 | 0.3790     | 51.20   | -0.6136       | -14.25  |
| 1 type of insulation                                    | 0.3563 | 0.0063     | 4.64    | 0.0156        | 2.06    |
| 2 types of insulation                                   | 0.1477 | 0.0317     | 19.84   | -0.0899       | -9.31   |
| 3 types of insulation                                   | 0.1633 | 0.0425     | 25.96   | -0.0461       | -5.13   |
| 4 types of insulation                                   | 0.0879 | 0.0550     | 27.75   | -0.0823       | -7.30   |
| Fully insulated   | 0.1206 | 0.0734     | 35.86   | -0.1366       | -11.61  |
| Attic   | 0.3178 | -0.0108    | -10.31  | -0.0209       | -3.14   |
| Basement  | 0.1401 | 0.0098     | 8.09    | 0.0279        | 3.90    |
| Heating: Gas or coal stove                              | 0.0970 | -0.0853    | -25.92  | -0.0155       | -0.78   |
| Heating: Boiler, district heating, fireplace or hot air | 0.8852 | 0.0166     | 5.40    | -0.1441       | -7.96   |
| Heating: Air conditioning or solar panels               | 0.0002 | -0.0335    | -1.31   | -0.7783       | -4.86   |
| Living: L-room  | 0.2423 | 0.0253     | 23.58   | 0.1807        | 28.32   |
| Living: T-Room  | 0.0054 | 0.0349     | 6.53    | 0.0682        | 2.10    |

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Table A.1 – Continued from previous page

| Variable  | Mean    | Coeff. Var | T-value | Coeff. W*Var* | T-value |
|---|---------|------------|---------|---------------|---------|
| Living: Z-room or U-room                                    | 0.0622  | 0.0062     | 3.57    | 0.1815        | 15.09   |
| Living: Through (sun) lounge                                | 0.1534  | 0.0034     | 2.75    | 0.2475        | 32.76   |
| Living: Room and suite                                      | 0.0277  | 0.0541     | 21.47   | 0.0924        | 5.00    |
| Garden: North   | 0.0919  | -0.0363    | -21.32  | -0.0144       | -1.37   |
| Garden: North East  | 0.0443  | -0.0306    | -14.10  | -0.1118       | -7.72   |
| Garden: East  | 0.1022  | -0.0349    | -21.03  | -0.0016       | -0.15   |
| Garden: South East  | 0.0763  | -0.0271    | -15.07  | -0.1281       | -11.24  |
| Garden: South   | 0.1795  | -0.0197    | -13.63  | -0.0899       | -10.67  |
| Garden: South West  | 0.1126  | -0.0143    | -8.90   | -0.1392       | -14.04  |
| Garden: West  | 0.1140  | -0.0311    | -19.41  | -0.0441       | -4.48   |
| Garden: North West  | 0.0577  | -0.0301    | -15.28  | -0.1266       | -9.46   |
| Monument  | 0.0042  | 0.1333     | 21.69   | -0.3491       | -7.65   |
| Fireplace possible  | 0.0081  | 0.0463     | 10.66   | -0.0049       | -0.14   |
| Fireplace   | 0.0704  | 0.0733     | 45.39   | -0.1634       | -14.94  |
| Unemployment benefits per 1000 inhabitants in neighborhood  | 36.9603 | -0.0014    | -54.80  | 0.0052        | 16.37   |
| Disability benefits per 1000 inhabitants in neighborhood    | 87.8439 | -0.0005    | -32.87  | 0.0016        | 19.26   |
| Percentage of inactive inhabitants in the neighborhood      | 15.4488 | -0.0002    | -5.29   | 0.0016        | 19.26   |
| Percentage of people aged between 15 and 24 in neighborhood | 0.1147  | 0.2274     | 21.00   |               |         |
| Percentage of people aged between 25 and 65 in neighborhood | 0.5215  | 0.0412     | 8.07    |               |         |
| Percentage of people aged 65 and over in neighborhood       | 0.1440  | 0.1485     | 23.26   |               |         |
| Population declined   | 0.5931  | -0.0151    | -17.92  |               |         |
| $W_a^*$ dependent variable                                  | 11.8746 |            |         | 0.5708        | 91.71   |
| $W_{tr}^*$ dependent variable                               | 11.6326 |            |         | -0.0001       | -0.33   |
| Appingedam  | 0.0077  | 5.0316     | 13.76   | 0.0233        | 2.62    |
| Bedum   | 0.0045  | 7.9360     | 17.04   | -0.0094       | -0.24   |
| Bellingwedde  | 0.0032  | 9.5654     | 17.70   | -0.1510       | -3.34   |
| Ten Boer  | 0.0053  | 6.0016     | 13.99   | 0.0153        | 2.26    |
| Delfzijl  | 0.0163  | 7.2881     | 25.14   | 0.0386        | 1.60    |
| Groningen   | 0.0917  | 4.9783     | 25.88   | 0.2500        | 15.65   |
| Grootegast  | 0.0060  | 8.3868     | 20.90   | -0.0521       | -1.55   |
| Haren   | 0.0170  | 8.7620     | 34.76   | -0.0628       | -2.98   |
| Hoogezand-Sappemeer   | 0.0225  | 8.0735     | 34.78   | -0.0296       | -1.53   |
| Leek  | 0.0112  | 9.2166     | 29.59   | -0.1145       | -4.40   |
| Loppersum   | 0.0057  | 3.4742     | 8.33    | 0.0365        | 2.42    |
| Marum   | 0.0037  | 8.7343     | 17.09   | -0.0769       | -1.80   |
| Stadskanaal   | 0.0112  | 9.8965     | 32.49   | -0.1738       | -6.83   |
| Scheemda  | 0.0065  | 7.8036     | 22.07   | -0.0065       | -0.22   |
| Slochteren  | 0.0091  | 7.9386     | 24.34   | -0.0078       | -0.28   |
| Veendam   | 0.0198  | 8.0089     | 33.43   | -0.0203       | -1.02   |
| Vlagtwedde  | 0.0062  | 8.9684     | 21.62   | -0.0974       | -2.81   |
| Skarsterlan   | 0.0158  | 8.3464     | 30.88   | -0.0363       | -1.61   |

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Table A.1 – Continued from previous page

| Variable                       | Mean   | Coeff. Var | T-value | Coeff. W*Var* | T-value |
|--------------------------------|--------|------------|---------|---------------|---------|
| Winschoten                     | 0.0126 | 7.4365     | 25.55   | 0.0263        | 1.08    |
| Winsum                         | 0.0090 | 6.7195     | 20.85   | 0.0921        | 3.42    |
| Boarnsterhim                   | 0.0107 | 8.6710     | 27.06   | -0.0699       | -2.61   |
| Zuidhorn                       | 0.0132 | 8.7113     | 30.89   | -0.0794       | -3.36   |
| Dongeradeel                    | 0.0078 | 7.6153     | 21.15   | 0.0192        | 0.64    |
| Achtkarspelen                  | 0.0110 | 7.0121     | 24.35   | 0.0646        | 2.68    |
| Ameland                        | 0.0013 | 7.9787     | 9.71    | 0.0117        | 0.17    |
| het Bildt                      | 0.0017 | 7.5950     | 9.57    | 0.0130        | 0.19    |
| Bolsward                       | 0.0030 | 8.7600     | 16.04   | -0.0730       | -1.60   |
| Franekeradeel                  | 0.0069 | 7.9012     | 19.23   | -0.0078       | -0.23   |
| Harlingen                      | 0.0064 | 9.2684     | 25.55   | -0.1152       | -3.80   |
| Heerenveen                     | 0.0266 | 9.8219     | 41.70   | -0.1628       | -8.28   |
| Kollumerland en Nieuwkruisland | 0.0047 | 7.9314     | 18.57   | -0.0132       | -0.37   |
| Leeuwarden                     | 0.0704 | 7.9851     | 39.48   | -0.0131       | -0.78   |
| Leeuwarderadiel                | 0.0039 | 9.5517     | 18.70   | -0.1451       | -3.39   |
| Lemsterland                    | 0.0076 | 9.9068     | 27.28   | -0.1637       | -5.38   |
| Menaldumadiel                  | 0.0047 | 10.1080    | 21.35   | -0.1954       | -4.93   |
| Ooststellingwerf               | 0.0139 | 10.4260    | 31.87   | -0.2155       | -7.89   |
| Opsterland                     | 0.0178 | 8.2315     | 30.67   | -0.0301       | -1.34   |
| Schiermonnikoog                | 0.0006 | 23.1576    | 17.13   | -1.2355       | -10.85  |
| Smallingerland                 | 0.0453 | 8.3269     | 41.68   | -0.0432       | -2.61   |
| Sneek                          | 0.0258 | 7.3645     | 30.23   | 0.0418        | 2.06    |
| Weststellingwerf               | 0.0086 | 10.2536    | 31.43   | -0.2023       | -7.40   |
| Nijefurd                       | 0.0045 | 8.7082     | 19.03   | -0.0733       | -1.91   |
| Assen                          | 0.0570 | 6.7460     | 32.46   | 0.0903        | 5.23    |
| Coevorden                      | 0.0267 | 11.7871    | 51.07   | -0.3346       | -17.43  |
| Emmen                          | 0.0716 | 8.7469     | 45.53   | -0.0801       | -5.05   |
| Hoogeveen                      | 0.0337 | 10.7991    | 51.23   | -0.2480       | -14.13  |
| Meppel                         | 0.0242 | 8.0443     | 33.79   | -0.0118       | -0.60   |
| Littenseradiel                 | 0.0045 | 8.2612     | 17.87   | -0.0357       | -0.92   |
| Geasterlan-Sleat               | 0.0048 | 9.7151     | 19.67   | -0.1551       | -3.75   |
| Wymbristeradiel                | 0.0082 | 9.1358     | 24.98   | -0.1054       | -3.44   |
| Wunseradiel                    | 0.0041 | 7.0052     | 14.57   | 0.0711        | 1.76    |
| Tietjerksteradiel              | 0.0220 | 7.9677     | 32.77   | -0.0115       | -0.57   |
| Pekela                         | 0.0070 | 9.0337     | 25.78   | -0.1141       | -3.88   |
| Eemsmond                       | 0.0063 | 5.5803     | 13.00   | 0.0181        | 2.04    |
| Reiderland                     | 0.0035 | 10.0931    | 20.31   | -0.2065       | -4.95   |
| De Marne                       | 0.0052 | 7.9910     | 18.75   | -0.0201       | -0.56   |
| Aa en Hunze                    | 0.0169 | 10.0868    | 38.55   | -0.1816       | -8.31   |
| Borger-Odoorn                  | 0.0167 | 12.1134    | 43.85   | -0.3589       | -15.57  |
| De Wolden                      | 0.0120 | 10.9228    | 38.29   | -0.2519       | -10.56  |

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Table A.1 – *Continued from previous page*

| <b>Variable</b> | <b>Mean</b> | <b>Coeff. Var</b> | <b>T-value</b> | <b>Coeff. W*Var*</b> | <b>T-value</b> |
|-----------------|-------------|-------------------|----------------|----------------------|----------------|
| Noordenveld     | 0.0229      | 10.4357           | 43.49          | -0.2128              | -10.62         |
| Westerveld      | 0.0127      | 11.3539           | 38.80          | -0.2902              | -11.84         |
| Ferwerderadiel  | 0.0027      | 8.2813            | 13.49          | -0.0438              | -0.85          |
| Tynaarlo        | 0.0231      | 12.2956           | 49.44          | -0.3651              | -17.56         |
| Midden-Drenthe  | 0.0220      | 12.0445           | 46.96          | -0.3520              | -16.43         |
| Dantumadiel     | 0.0045      | 9.0774            | 19.64          | -0.1086              | -2.81          |
| Menterwolde     | 0.0060      | 7.6370            | 19.47          | 0.0112               | 0.34           |

\* Cross-sectional averages for municipalities

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