

# 1 Introduction

We consider data on the gas consumption of dwellings of various types throughout North-East England. We have data on the gas consumption, age of the property, type of property, floor area of property, depth of loft insulation, whether cavity wall insulation is fitted, and whether a new boiler has been installed.

All but the gas consumption data is categorical, meaning that for example we do not know the precise age of the property but rather that it lies in a range of ages. This will impact our analysis and make it somewhat less accurate, but is a common trade-off, as it is easier to collect and store data of this sort. Obviously the type of property must be categorical, for example. We must note that the gas consumption has been somewhat severely rounded, resulting in artificially common values, especially on the higher end.

We will note that the gas consumption has been pre-corrected for weather, so this will not be a factor in our analysis. The data has also been selected to be representative of the housing stock, which will allow for us to draw more general conclusions. When we refer to a ‘unit’ of gas we mean 1 kWh per year.

## 2 Statistical Analysis

### 2.1 Handling the Missing Data

First we must check the data for missing values and decide how to continue. An aggregate plot of the data is found in Figure 1. Obviously one must think about the ramifications of this, but we can clearly see that a large proportion of the data for loft insulation is missing, making it somewhat less useful for our analysis. We assume a completely random missing data mechanism, as this is the most likely given the nature of our data. This means that using predictive mean matching should give us results that are unbiased. We will use this going forward.

Another way of dealing with missingness in categorical variables is to make NA a category. This is not what we are going to use, but it is a simple way of getting the analysis to work.

We use the R package `mice` to perform multiple imputation on our data to obtain a full dataset. The implementation of predictive mean matching that is used selects randomly from the 5 nearest neighbours (defined by squared difference in predicted value), so we fix our random seed to get repeatable results.

### 2.2 Initial Analysis

There are a few factors that we will account for. The first is that houses are not lines, but (nearly) cubes. We must consider that a house loses heat primarily through its four enclosing walls and its roof. One could think that a four fold increase in gas consumption would be needed to heat a house that is twice larger in length and depth. This means that it would be appropriate to use a square-root transformation on the gas consumption.

The decision to use the square root is validated by looking at the Q-Q plots in Figure 3. We see that the plot for the transformed response variable gives us superior results. We will continue with our analysis using the transformed response. We see that our data is heavily tailed. It has a very severe right tail which we ameliorate by taking the square root. This is due to the rounding of values creating large instantaneous increases in density, which violate normality assumptions. Hence much of our analysis will be of ‘root units’, which we square to get back our initial units of kWh.

Looking at the data given in Figure 2 we see that the median gas consumption is 13000 units. We see that the distribution is skewed and heavily tailed (yet more reason to take the root transformation). We see that the median consumption is similar across age bands and very different across floor area bands and property types. This should be reflected in our conclusions.

### 2.3 Model Comparison and Selection

First we example the independence of our variables. We do this using the  $\chi^2$  test, the results of which are given in Table 1a. We see that many of the variables are interdependent, which will influence our results. We see that the age, type, and floor area of a property are highly related, which is what we expected. We regress the square root of the gas consumption on all of the predictors to obtain our full model. The diagnostic plots are given in Figure 4. These plots are sufficient to make general predictions.

We will now compare the full model to two sub-models. The sub-models regress gas consumption on either the base property (age, type, floor area) and on modifications to the property (loft insulation, cavity wall insulation, new boiler). The diagnostic plots are given in Figure 5. The plots show that both are valid models which give similar results to the initial model. We compare them to the initial model using an ANOVA test. We see that the modifications model is significantly different from the initial model, so the base properties of the property have significant effects. The property model is not statistically significantly different from the full model. We compare the residual sum of squares (lower is better) and see that

the full model has an RSS of 1244518, the property model has an RSS of 1248346, and that the modification model has an RSS of 1880124. The modifications to the property have a significantly lesser effect on the consumption than the properties inherent to the property. Looking at the Q-Q plot for the modification model one may think it is a better model. This is false; the Q-Q plot looks this way as the model is unable to predict the values that are more common and thus distort the plot.

We choose to use the full model for our analysis as we wish to see the effects of the modifications on the property, as these are measures that can be taken after a property is constructed. The regression coefficients are given in Table 1b. These are the expected difference in root gas consumption from the ‘baseline’ of a property with given characteristics.

### 3 Discussion of Results

We are discussing the effect of the different variables on the square root of the gas consumption. The ‘baseline’ results (as given in Table 1b) are for a Bungalow in age band 1, in floor area band 1, with loft insulation greater than 150mm, without cavity walls, and without a new boiler. The predicted square root of consumption for this property is 103.7. If for example we had a semi-detached house, with a new boiler, no cavity walls, more than 150mm of loft insulation, with floor area 3, in age band 3 then our new predicted root consumption would be

$$103.68 - 3.58(\text{age}) + 0.75(\text{semi-detached}) + 30.27(\text{floor area}) - 2.78(\text{New boiler}) = 128.34 \text{ root units.}$$

It must be noted that these numbers cannot be taken independently of one another: all factors must be accounted for for the model to be remotely valid. This means that one cannot say that all flats are more efficient than all bungalows: one must specify the configuration of each to make a comparison.

#### 3.1 Effect of Age

We see that age has less of an effect than might be expected. The first four age bands have minimal effect. The fifth and the sixth age bands have more significant differences, with a decrease on average of 7.84 and 13.76 respectively. This means that new builds have decreased gas consumption. This may be due to the types of property built in new builds, as in Table 1a we see that they are not independent.

#### 3.2 Effect of Type

We see that the type of property is very significant in determining the gas consumption. Detached houses have an increased root gas consumption compared to bungalows, consuming 12.7 root units more. Semi detached consume only very slightly more, to the point that it is not significant (it is less than the standard error of the estimate). Terraced and end of terrace houses consume less. Flats consume significantly less, with 22.9 less root units on average, corresponding to 525 units less on average.

#### 3.3 Effect of Floor Area

We see that floor area has a significant effect on the gas consumption. All of them are significantly different from each other. The largest floor area consumes on average 52.56 root units, or 2762 units on average more than the smallest floor area. This is also not independent of the type of property, so we must know that changing one should have an effect on the other (ie a property with a large floor area is less likely to be a flat than detached).

#### 3.4 Effects of Modifications to The Property

These effects are smaller, so will be discussed in conjunction. First we note that we see in Table 1a that all of the modifications are largely independent of each other. This meshes with what we expect. We see that a new boiler decreases root gas consumption by 2.78, corresponding to an average decrease in consumption of 7.71 units. Adding cavity wall insulation has no appreciable average effect on gas consumption. Adding loft insulation above 150mm decreases root gas consumption on average by 1.98 units, corresponding to an average decrease of 3.90 units of gas consumption. We see that the standard error is equal to the estimate, so we can only really be sure that it has a small positive effect on average, and not the exact value of that effect.

## 4 Conclusions

We can conclude that if we want to decrease gas consumption we should build small flats with good insulation (loft and cavity wall) and new models of boiler. This is a foregone conclusion, but we now have numbers to back it up. A modern flat (age band 6, floor band 1) consumes 6000 fewer kWh per annum on average than an average house (mid-terrace, age band 4, floor band 2, no cavity wall, bad loft insulation, old boiler). This is a saving of approximately £230 per year (UK average price per kWh of gas is 3.8p).

We cannot make any inferences as to why these changes make an effect from the model; the model only tells us the effect that they have. In this case it is somewhat obvious as to why the variables have the effects that they do, but it is often not. For example, flats are likely more efficient as they benefit from a collective heating effect in which flats are warmed by others around them. This is not present in detached houses. We know this from common sense, but this is not explicitly reflected in the model.

## A Plots and Figures

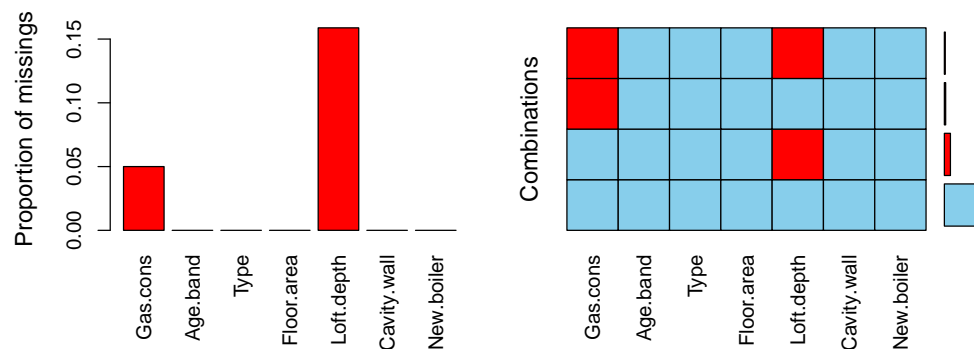


Figure 1: Aggregate plot of missingness in our data

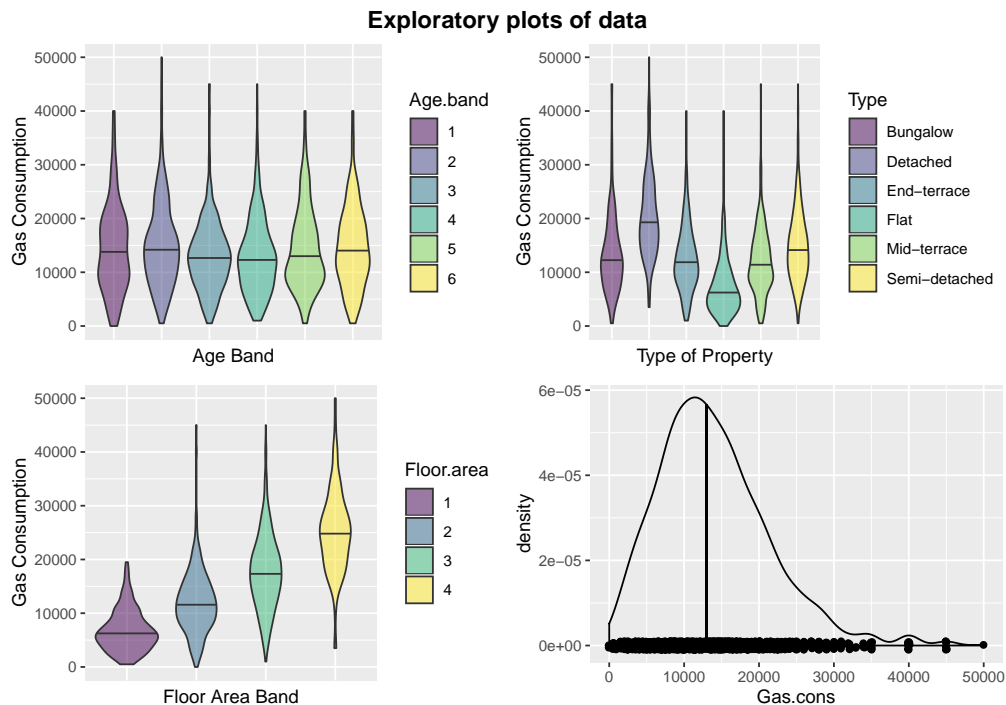


Figure 2: Visualisation of data relating to gas consumption

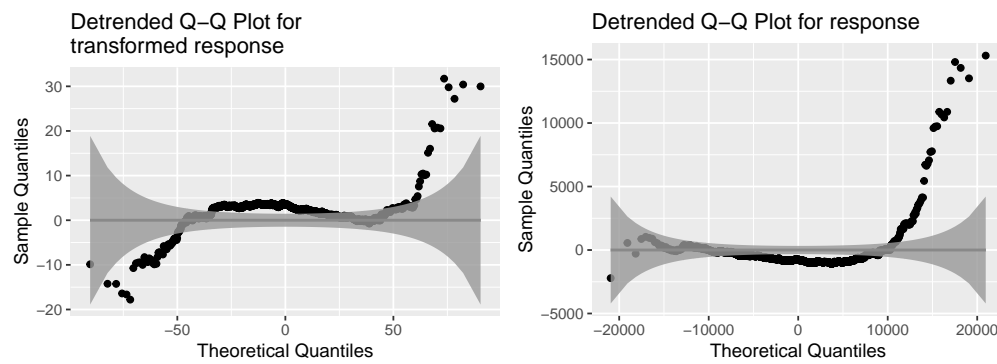


Figure 3: Model Q-Q plots for the transformed and non-transformed models

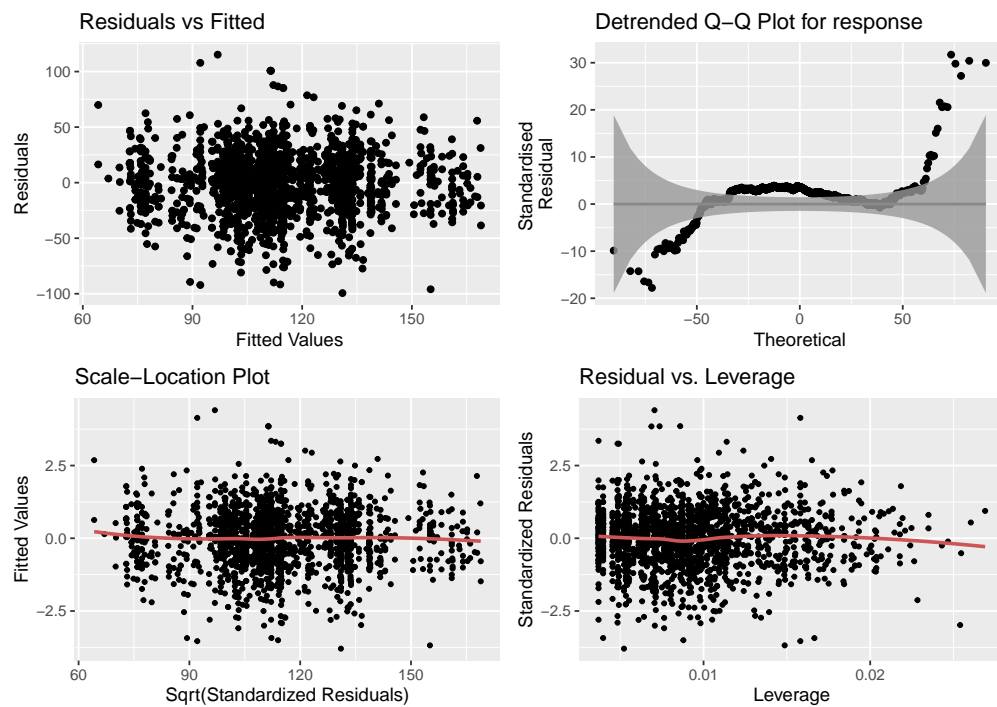


Figure 4: Model diagnostic plots for our full model

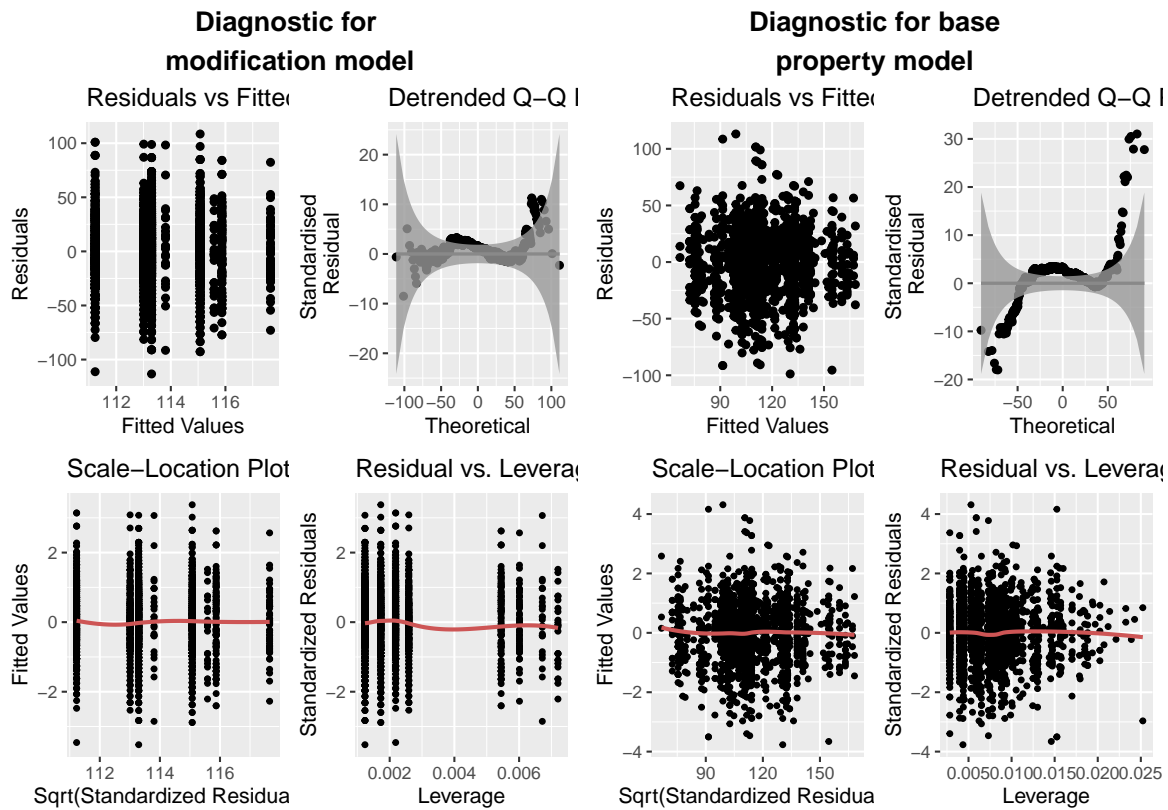


Figure 5: Model diagnostic plots for our sub-models

## B Tables

Table 1: Tables relating to model fit and variable independence

	Variable 1	Variable 2	P-value
1	Gas.cons	Age.band	0.03
2	Gas.cons	Type	0.00
3	Gas.cons	Floor.area	0.00
4	Gas.cons	Loft.depth	0.55
5	Gas.cons	Cavity.wall	0.12
6	Gas.cons	New.boiler	0.31
7	Age.band	Type	0.00
8	Age.band	Floor.area	0.00
9	Age.band	Loft.depth	0.00
10	Age.band	Cavity.wall	0.00
11	Age.band	New.boiler	0.23
12	Type	Floor.area	0.00
13	Type	Loft.depth	0.72
14	Type	Cavity.wall	0.00
15	Type	New.boiler	0.16
16	Floor.area	Loft.depth	0.87
17	Floor.area	Cavity.wall	0.00
18	Floor.area	New.boiler	0.35
19	Loft.depth	Cavity.wall	0.68
20	Loft.depth	New.boiler	0.08
21	Cavity.wall	New.boiler	0.49

A p-value less than 0.05 means variables are (likely to be) statistically dependent.

(a) Table of results from Chi Squared test for independence.

	Term	Estimate	Standard Error
1	(Intercept)	103.68	4.06
2	Age.band2	-0.96	2.37
3	Age.band3	-3.58	2.27
4	Age.band4	-4.84	2.34
5	Age.band5	-7.85	2.87
6	Age.band6	-13.76	2.95
7	TypeDetached	12.66	2.88
8	TypeEnd-terrace	-5.97	2.74
9	TypeFlat	-22.92	3.11
10	TypeMid-terrace	-11.70	2.33
11	TypeSemi-detached	0.75	2.08
12	Floor.area2	11.38	3.31
13	Floor.area3	30.27	3.62
14	Floor.area4	52.56	4.56
15	Loft.depthLe	1.98	1.98
16	Cavity.wallY	-0.09	1.31
17	New.boilerY	-2.78	1.34

(b) Table of regression coefficients for the full model.