

Machine Learning with Domestic Energy Use Data

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Abstract

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Chapter 1

Introduction

1.1 Introduction

Amidst international pressure on countries to reduce their carbon footprints [1] and the British public's becoming increasingly frustrated by rising energy bills with little to no explanation as to the reasons behind the increases [1], the UK Government is currently executing an £11bn plan to distribute 53 million smart meters to over 30 million households and small businesses across the country by 2020¹. Smart meters, which measure a household's gas and electricity consumption in real-time and regularly communicate the readings directly to the utility companies, are expected to help households reduce energy usage by displaying on an in-home monitor how much energy is actually being used, often on a per-appliance basis. They should also increase transparency in the household's energy bills by eliminating the need for monthly meter readings and estimations by the energy providers. This should result in an average household savings from £23 to £42 per year, but does not include an estimated £7 per year surcharge which will be hidden in customer bills. Instead, the energy companies will be sent documented accountings of their customers' real consumption, and as a result, will be able to invoice more accurately.

While there has generally been strong support for the smart meter program [2], there has also been resistance to the campaign, with fears that the energy companies will use the information as an opportunity to raise their customers' bills and increase their own profits [3, 4]. These fears are not completely unfounded, as companies such as SAS have already started marketing services that are "for energy companies that are serious about turning [customer] information into vital insights and competitive advantage... where the information comes into its own is around customer retention, targeted marketing and increased profitability... targeting customers based on actual behaviour" [5]. Equally, if not more importantly, are concerns that have been raised regarding the security risks associated with transmitting consumption data across an open network [6, 7]. Specifically, how much other information about a household can be inferred from energy consumption readings?

In looking to answer whether these fears are well-founded, the aim of this project is to explore whether (and to what extent) it is possible to construct features that predict detailed personal information about a household based on its

¹However only 80% is actually expected to be completed by 2020

energy consumption readings, and if so, if the results would be reliable. Breach of privacy issues would include whether such intrusive knowledge of household habits could effectively be exploited for targeted marketing or advertising campaigns, such as those promised by SAS, Big Brother-type government “watching”, or equally if not more maliciously, for timing burglaries or other crimes.

Using electricity consumption information collected by the Household Electricity Survey (HES), a DEFRA² and DECC³ sponsored national survey of energy use collected over a period from 2010 to 2011, classification models are created to predict two properties of households: (1) The presence (or absence) of children and (2) the Ipsos MORI social grade of the chief income earner. These properties are chosen because, of all the information gathered by the HES survey, they would logically be of interest to someone who might wish to intrude on a household.

This project has 3 main components:

1. Clean the HES data and create a database that stores each households’ energy-use information and any other relevant data;
2. Extract useful features from the data that can be used as inputs to a classification model;
3. Build models to infer household properties using supervised learning methods.

1.2 Smart Meters

1.3 Related Work

Particularly in recent years, an increasing number of studies have applied machine learning and data mining techniques to model and analyse domestic electricity consumption. This field of research is of particular interest to energy providers, as understanding who their clients are and how and when they use energy lets the providers optimise their resources (providing more power during peak times and less during periods of low demand), and create and market products to specific client groups. The research done using household energy data can be broadly separated into two categories, either: 1) only consumption data is analysed to categorise households or 2) the data is related to additional information about the household. The first approach imposes fewer requirements on the data itself and has therefore been used in unsupervised tasks [8]. For example, Chicco, in a study analysing electrical load pattern data, gives an overview of the clustering techniques used to establish suitable client groups [9]. Cao et.al also grouped consumers using electricity load profiles, however they focused on finding households with the same peak usage [10].

Another popular area of research is NILM (*non-intrusive load monitoring*), which involves taking aggregated energy consumption data from households and disaggregating it to find the load used by constituent appliances. Kolter and

²Department for Environment, Food and Rural Affairs

³Department for Energy & Climate Change

Jaakkola employed factorial hidden Markov models (FHMMs) to disaggregate energy readings, achieving more than 90% precision on a synthetic data set [11]. Similarly, a study performed by Lisovich et.al. used NILM to determine when people were present in a household, the appliances they were using (and when), and their sleep/wake cycles. This was done by looking at a dataset of dwellings that had energy readings taken at either 1 or 15-second intervals for between 3 and 7 days. Compared to the dataset used in this report, however, the households in the Lisovich et. al. study were more homogeneous, particularly with respect to appliance types (e.g., none of the Lisovich et al. households used electric showers or water heaters) [7].

McLoughlin et al. explored the correlation between electricity consumption data and household characteristics using a dataset of smart meter readings taken from 4,232 Irish households. They also investigated methods for clustering households based on energy use. Beckel et al., with the same dataset as McLoughlin et. al, used supervised learning methods to classify household attributes. Their research involved predicting a set of characteristics describing the inhabitants, such as the age of the chief income earner, presence/absence of children and socio-economic status. They also sought to identify properties of the dwelling itself, including the number of appliances and bedrooms, and the types of cooking facilities [8]. In contrast to the Beckel et al. study, the work being presented here, while tackling some similar issues, considers a different set of classifiers (random forest, logistic regression and Knn) as well as a new class of features taken from the time-frequency transform of the data. Another distinction is that, to boost performance, Beckel et al. considered models that relied on *a priori* knowledge beyond that available from electricity metering alone, whereas no other prior knowledge outside of the data recorded by the smart meters is assumed in this report. Finally, while Beckel et. al. used a dataset of Irish households, the HES dataset contains only English residences. This distinction is important because variations in smart meter implementations from country to country means that the results obtained by Beckel et. al. are not necessarily transferable to Britain [4, 12].

1.4 Project Description

The goal of this project is to address the privacy concerns that have been raised regarding smart meter data. More specifically, this project looks at whether it is possible to create a probabilistic model that can automatically predict intimate information of a household given only features that can be extracted from the data available from smart meters. Supervised learning methods were used predict the socio-economic status of a household and whether there are children present in that household. It is argued that, while it is possible to construct a model that infers household characteristics, numerous factors contribute to the way in which a household uses energy including.

The remainder of the report is structured in the following way: First, the HES dataset is introduced, which contains labeled electricity consumption data of 250 households. The steps performed to pre-process the data are presented along with challenges encountered and issues that needed to be accounted for with regards to the dataset. Next, the methods used to extract features from the

HES dataset are outlined and feature selection methods are discussed. Following this, the classification models introduced and optimized before discussing their performance on unseen household data. Finally, the results are compared to those obtained by similar studies and the original question regarding privacy invasion is discussed in relation to the results obtained.

Chapter 2

Data

2.1 Overview of the HES Dataset

The data used in this project came from The Household Electricity Survey (HES), a UK-government sponsored study of residential energy usage jointly commissioned by the Department for Environmental, Food and Rural Affairs (Defra) and the Department of Energy and Climate Change (DECC). Britain's most detailed look at energy consumption in the home environment to date [A], HES tracked the electrical power demands and sources of energy utilization in a variety of owner-occupied homes in England over the period May 2010 to July 2011 [13]. The study sought to identify, catalogue and monitor the range, quantity and energy demands of appliances found in 'typical' British homes, with the underlying aim being to better understand households' frequency and patterns of electricity usage, and to collect any 'user habit' and/or other socio-economic data that might emerge. [14]. This information would be plied in a variety of ways and purposes, not the least of which would be as an aid in developing energy policy (both at the consumer and energy provider levels), and to help justify the £12bn smart meters roll out.

The HES study monitored 250 households, of which 26 were observed for one year, and the remaining 224 for roughly one month. Although all the participating households were located in England, they did not share the same demographic or geographic profiles. This was reflected in the wide spectrum of number and ages of appliances. Whereas one household, for example, registered just 13 appliances, another had 85. There was a forty-one year old freezer, several brand new televisions and a broad assortment of ages and types of devices in between. [B] When aggregated, (as outlined in Section 2.2), the result could be considered an estimate of an average mains reading.

Smart meters record the total energy being used in a given interval, whereas when discussing individual appliances, it is common to talk about the energy used per unit time (i.e power). For example, an average kettle might use 3kW of power. If the kettle is running for 2 minutes then the energy used would be 6kWh (kilo Watt minutes). A potential issue arises when we consider another appliance that uses less power but for a longer period of time. A hairdryer, for instance, uses 1kW of power. If a hairdryer was being used for 6 minutes, then the total energy used also be 6kWh. Although the hairdryer uses less power than the kettle, the smart meter reading would record the same number (6kWh). The

Smart meters used in the HES study took readings either every 2 minutes or every 10 minutes in units of deciwatt hours (dWh or 0.1Wh). This is a measure of the total energy that the home consumed since the last reading. As it is conventional to describe the energy consumed in terms of kilowatt hours (kWh), the readings are each multiplied by 10,000.

In addition to the data collected on appliance types and the meter readings, participating households also kept diaries of how they used their mains appliances, and provided supplemental information about the household and its constellation, such as: the number of occupants, employment status, Ipsos MORI social-grade and whether there were children present.

2.2 Extracting the Data and Pre-Processing

As explained in Section 2.1, electricity readings from individual appliances and sockets were taken for each household. This was in contrast to the total-energy-consumed figures needed for this project. In organizing its data, the HES study assigned values to the 250 possible appliances that the designers of the study expected a household to have. Appliances that were not present in a household were designated a 0. The resulting raw data was held in large csv files. Since no household had all 250 potential appliances, there were a significant number of redundant entries. In order to use the data to perform data mining, therefore, numerous pre-processing steps needed to be performed. This was accomplished by writing and implementing python scripts with embedded SQL.

Specifically, the first step in pre-processing the data was to create a MySQL database and import the appliance readings into a table. Cambridge Architectural Research Ltd (CAR) [15], an architectural consultancy, provided additional files that mapped which appliances needed to be aggregated for each household to arrive at an estimated mains reading, as this was often not simply the sum of all appliances readings. A table was therefore created for every household where each row contained the aggregated electricity measurements for a given date and time.

Another consideration was the number of participating households. 250 is a relatively small number for a machine learning task, since they would probably not produce enough data to build models that would accurately sample the population. To help account for this, the 26 households that were monitored for an entire year were split into 12 instances that could be treated as separate households. This generated an additional 281 household instances. While it did not create a more diverse group, it did add more instances to train and validate, as well as with which to test a classifier. To avoid overfitting the classification models to the data, all instances from the 26 (split) households were either in the training or test set, but never in both.

The inconsistency in measurement intervals alluded to at the beginning of this section also had to be rationalised. While some households reported how much energy they used every 10 minutes, others were measured in 2-minute intervals. To create consistency in the data, for the ‘2-minute households’, every five intervals were summed so that all the households had 10 minute granularity. This step was important because some of the consumption features would have been affected by differences in measurement intervals. Once all the households were represented

in terms of 10-minute intervals and in units of 0.1Wh (deci Watt hours), each reading could be multiplied by 1000 to convert the data to kWh.

The last stage in pre-processing was to ensure that each instance was of the same duration, with each day of the week occurring the same number of times across households while still maintaining being ordered by their point in time. The justification for this is as follows: When visualising the data, temporal structure was observed both intraday and intraweek. It was noted that in addition to an obvious daily pattern (more energy being used during the day than at night), there was also a repetition over weekly cycles, where it was possible to distinguish some days of the week from others as a pattern emerged every 7 days. Ensuring each household had an integer number of weeks would mean that no single day of the week would effect the total energy used by the household. For example, it emerged that more energy is used on Sundays than other days of the week. If one household had three occurrences of a Sunday while being monitored while another had four occurrences of a Sunday, then when computing features such as the average daily energy would be different for the two households simply due to the extra Sunday. Because more households were recorded for roughly one month, it was decided to ensure that the data for each household was 28 days long (4 weeks). Furthermore, it was important to ensure that the days of the week remained in order (i.e that a Monday was followed by a Tuesday, which is followed by Wednesday etc.). This is because some features, such as computing the Fourier transform, expect the data to be in sequential order. Finally, the data was made to start on the same day of the week for each household as this made it far more convenient to extract specific parts of the data.

1. Ensure that each household has an integer number of days by topping and tailing the data.
2. Find the mode day of the week that the data starts from (this was found to be Sunday).
3. For the households that do not begin on a Sunday, chop the top few days so that the data begins on a Sunday.
4. If the household's data is now less than 28 days, append days-to-the-end until it is of the correct length. If it is possible, use the days that were chopped off in the previous step, otherwise, reuse a day's worth of readings.

Figure 2.1 gives a visual example of data that has been made to be of uniform length. As the readings start on a Thursday (Day 5), the first three days are chopped off the top. Since the data is now less than the required number of days, days are either reused or, if possible, taken from the days that have been chopped from the top¹.

¹It was noted that this method does create a bias in the features. For example, when computing the average energy used on a Monday, if a household only has three unique instances of a Monday and one instance has been reused, then this will affect the feature.

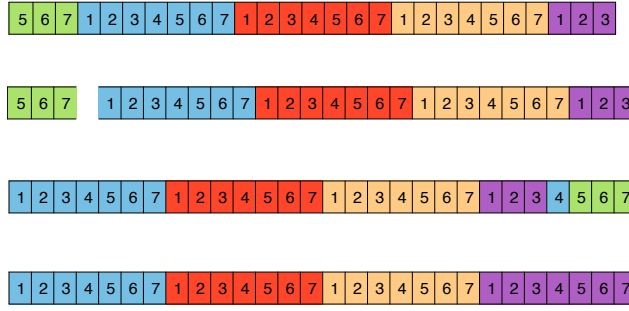


Figure 2.1

2.3 Household Classes

Each household that participated in the HES study completed a survey with questions about the building they occupied (such as the year the house was built), the household itself (such as the number of occupants) as well as their attitude towards climate change and energy consumption. The answers to these questions are used as labels for the households to perform supervised learning.

Social Grade	Description	Sample Size	% Sample	% Population
A	High managerial, administrative or professional	33	6.4	4
B	Intermediate managerial, administrative or professional	95	18.3	23
C1	Supervisory, clerical and junior managerial, administrative or professional	197	38.0	29
C2	Skilled manual workers	128	24.7	21
D	Semi and unskilled manual workers	34	6.6	15
E	State pensioners, casual or lowest grade workers, unemployed with state benefits only	32	6.2	8

Table 2.1

Tables 2.1 and 2.2 show the sample sizes for each class of the two classification problems being considered in this project. The distribution of households over each of the classes in our sample is similar to the true distribution, which means that the empirical prior probability of each class is a reasonable estimate of the true prior probability. However, there is a significant imbalance in the classes, especially in the socio-economic classes. This result in bias in the classification models that will need to be considered when evaluating them.

Class	Sample Size	% Sample	% Population
Children	187	36	39
No Children	332	64	61

Table 2.2

2.4 Discussion

After the data had been extracted from the csv files, pre-processed and imported into MATLAB, plots of the data were made in order to visually gain insight into how households used energy and increase domain knowledge. Figures 2.2 and 2.3 are examples of how some of the households consumed energy. Both figures show the data gathered from the same households, but over different time periods. Studying these plots gives valuable insight into the households which is used later to aid in feature extraction, as well as ensure that the data appears reasonable.

In figure 2.2, the first thing to be noted is that the consumption is not smooth. There are sharp peaks that vary in height, which can be used to make assumptions about which appliances are being used. For example, many of the peaks are around 1kW, which is roughly the amount of power used by a kettle. The next thing to note is that there is an obvious underlying daily repetition. The household tends to use more electricity at night than it does during the day time. Finally, it can be seen that the energy consumption on weekends is slightly different than that of week days, particularly, there are short periods of abnormally high electricity on Saturdays and Sundays which are observed less frequently during the week. To see this, note that both figure 2.2 and 2.3 start on a Sunday, and that each ‘wavelet’ is one day long.

It is a result of these observations that the data was made to be four weeks long. Ensuring that each day of the week appears exactly 4 times for each household means that features such as the total energy used is not influenced by which days of the week are present.

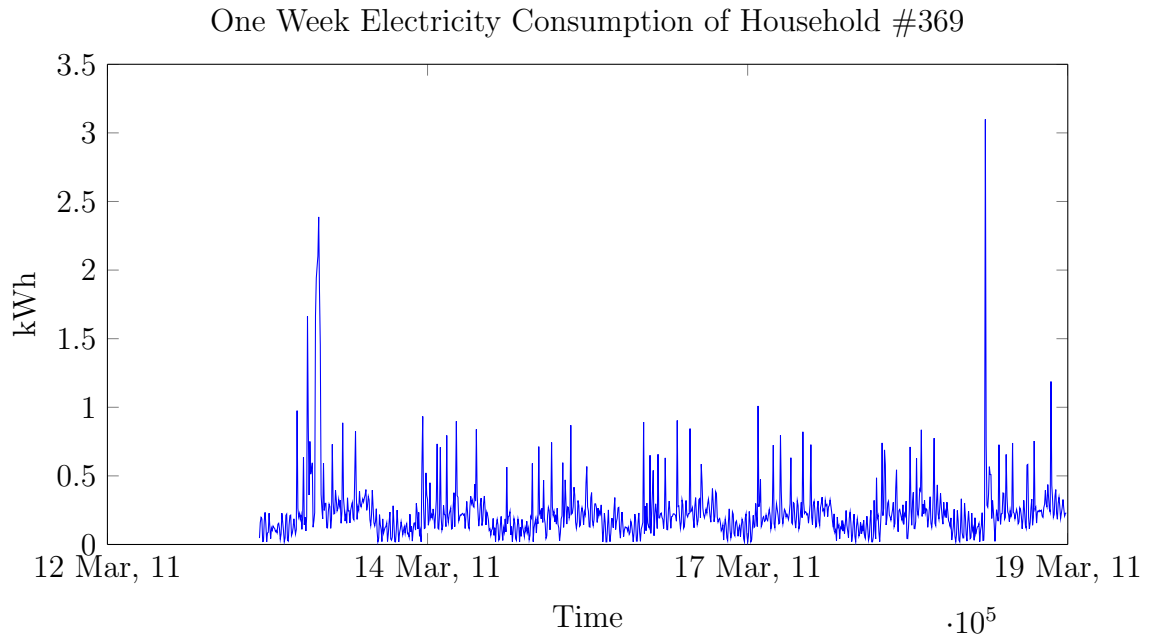


Figure 2.2: The electricity use of household No.369 over a week after being pre-processed

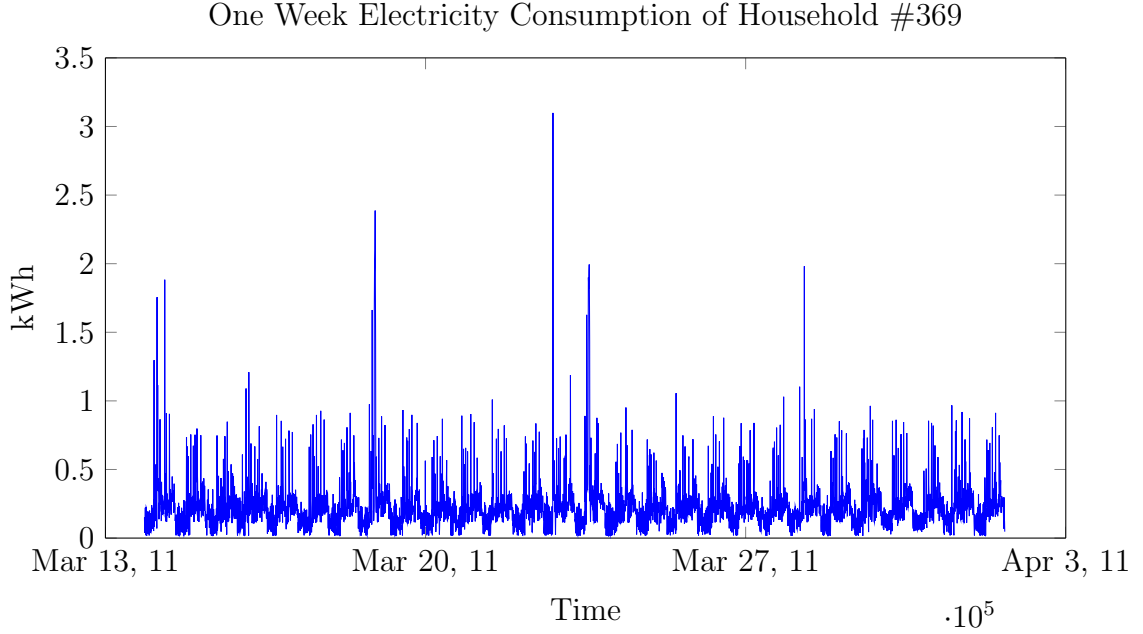


Figure 2.3: The electricity use of household No.369 over a four week period after being pre-processed

2.5 Issues

As with any study, several issues arose which needed to be recognised and dealt with. These were invariably related to the data. Some were simply the result of environmental influences, while others reflected the methodology used in conducting the study. Those most relevant to this project are outlined below; more can be found in the CAR report [14].

The first problem with the data concerned the number of households that participated in the HES study. Comparing the UK's 250 households to, for example, the 4,232 that took part in Ireland's CER (Commission for Energy Regulation) study of household electricity consumption ² (used by Beckel et. al. and McLoughlin [16, 17, 8, 18]), it is less likely that the UK results generalised as well as the Irish ones, particularly for the multi-class classification problem (where there are as few as 32 households per class).

Moreover, only English homes were included in UK study (i.e, Scotland, Wales and Northern Ireland were not represented), and all of the houses were owner-occupied. While 84% of the British population does live in England, only 64% of homes in England are owner-occupied [19]. As such, the subset of participants considered in the HES study was not fully representative of the UK as a whole. It is important to remember, however, that the aim of this project was to determine *whether it was possible* to infer a household's properties from its electrical power consumption, not to build a classifier that could be used to infer British household properties from smart meter data. The distinction being that this is a proof-of-concept project that looks at whether information about a household is contained in the energy use patterns, rather than an attempt to build a commercial product. Therefore, the quality of the sample population households (or lack thereof) is

²www.ucd.ie/issda/data/commissionforenergyregulationcer/

not detrimental to the aim of this project.

A more bothersome issue involved the quality of the data that was gathered during the HES study. Looking at the household in Figure 2.3 it credibly shows the characteristics of a typical home’s consumption; it is one of the ‘better’ households in the sample. There are many others, however, that do not follow the same kind of trend, such as the two presented in Figure 2.4. Either they do not have the same well-defined periodicity, or they may use significantly more (or less) energy than the average household. In these cases, the task then became to find a means of determining whether these discrepancies were reasonable differences that could be attributed to variations between households, or whether they were the result of poorly executed data collection. Since the HES study involved recording individual appliances, rather than the mains reading of a household, the total energy consumed by each household could not be given with certainty (as it was not definitively known whether all appliances and sockets in a household were recorded). This complication is made evident in Figure 2.4 where Household #75 is always using at least some energy while Household #121 sees its consumption drop to 0. Household #75 serves as a better estimate as it is reasonable to assume that there will always be a small amount of electricity used by a home since appliances are not 100% efficient and usually leak electricity.

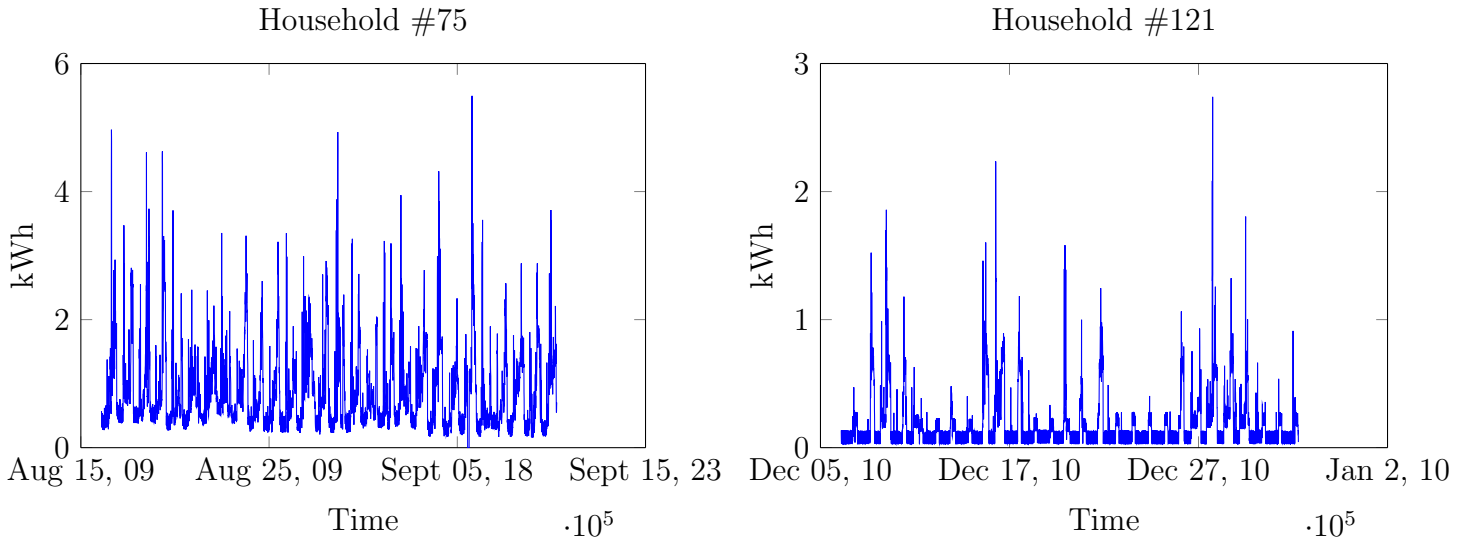


Figure 2.4: The electricity consumption of two households that do not show the same pattern of consumption as other households

Table 2.3, is taken from a Center for Sustainable Energy [20] report and shows how much power various appliances use. Comparing these values to the data from the meter readings, it is reasonable to see a household use anywhere from 50W to upwards of 15,000W. However, the chart also indicates that some of the most expensive appliances (which have large effects on a households’ consumption) are not always present in all households. These include electric cookers, electric showers, electric heaters and tumble driers. In the HES study, only 38 of the 250 households used electric water heating. While it could be expected that these factors would impact a household’s consumption, and knowing this would aid in classifying the households, it was left to be worked out independently, as the so called *disaggregation problem* (see section 1.3) is a popular topic of research in and

of itself.

Table 2.3: **Energy used by various household appliances**

Appliance	Rating	Appliance	Rating
Immersion heater	3,000W	Fridge	40-120W
Electric fire	2,000-3,000W	Fridge-freezer	200-400W
Oil-filled radiator	1,500-2,500W	Freeze	150W
Electric shower	7,000-10,500W	Electric mower	500-1,500W
Dishwasher	1,050-1,500W	Electric drill	900-1,000W
Washing machine	1,200-3,000W	Hairdryer	1,000W
Tumble dryer	2,000-4,000W	Heating blanket	130-200W
Toaster	800-1,500W	Games console	45-190W
Kettle	2,200-3,000W	Laptop	20-50W
Microwave	600-1,500W	Desktop computer	80-150W
Oven	2,000-2,200W	Tablet (charge)	10W
Grill/hob	1,000-2,000W	Broadband router	7-10W
LCD TV	125-200W	Smart phone (charge)	2.5-5W

In examining the data closely, a small number of instances could be noted where the electricity usage for selected households showed consumption levels either flat-lining or completely disappearing for one or more days. To compensate for this anomaly in the data, the usage patterns for each affected household before and after the aberration were analysed and compared to the event. In most cases, it was possible to visually determine whether the incongruity was most likely related to a residence being unoccupied (i.e., the family were on holiday), or if it was due to some technical issue(s) linked to the energy readings themselves (i.e., the meters presenting erroneous data). A decision was taken to discard households with a consumption reading of 0kWh when that reading represented a statistically significant proportion of the total time for which the household was being observed. If a reading for a single day appeared completely out of keeping with all the other readings for that household, then that day's data was discarded and replaced by an equivalent day from another trial week.

The next factor that needed to be considered was the effects of weather, the time of year in particular. Colder temperatures and shorter periods of sunlight during colder months have been shown to precipitate higher electricity usage. [21]. Although CAR was able to provide a document outlining which appliances needed to have their readings adjusted to account for seasonal factors, these did not appear to be well-reasoned, and didn't include many of the appliances used by households in the study. Since most households were recorded in the colder months between November 2010 and April 2011, and those that were measured for a year didn't appear to significantly change their consumption in the warmer months, seasonal adjustments were disregarded.

Chapter 3

Feature Exploration and Extraction

3.1 Types of Features

When data mining in time series, consider each point in time sequentially is not usually sufficient. Aside from ignoring the high dimensionality of the data, it does not account for the correlation between consecutive values [22]. It is therefore beneficial to transform and aggregate the data in such a way as to reduce the dimensionality as well as capture differences in consumption patterns between classes.

According to Beckel et al. [17], features of interest when classifying households based on energy consumption would include: consumption figures, ratios, temporal properties, and statistical properties. Consumption figures represent the average, maximum and minimum amount of energy used over a defined period of time. Ratios are features that calculate the fraction between the consumption figures; they capture relevant patterns that occur across points in time. Temporal features express the first or last occurrence of some event, the time at which the daily maximum or minimum energy demand takes place, or any periodicity within the household's electricity consumption. Finally, statistical properties, such as variances or correlations, give insight into the consumption curve and demonstrate how a household's activity may fluctuate throughout a predetermined time period.

3.2 Non-Linear Transformation

Numerous statistical methods presume that input data follows a normal distribution. With this in mind, the HES data was visualized and compared against a normal quantile plot to find suitable non-linear transformations [23] [24]. Figure ?? shows the normal quantile plot of the average standard deviation of a household on Mondays (left) and the logarithm of this feature (right). The linearity of the sample quantiles of the features (x-axis) versus the theoretical quantiles of a normal distribution (y-axis) implies that the transformed features are (roughly) normally distributed. These transformations are important for classifiers, such as k-nearest neighbour, which rely on the distance between samples based on their

features.

3.3 Creating Features

One method of extracting features is to compute as many different types as possible, compare them all and then choose those that best discriminate between classes. Applying this to households, in addition to considering the energy used over a month, data could be further split into weeks, days and even hours. Consumption figures and statistical properties would then be calculable for each of these intervals. While this method does provide more coverage, and thus a greater probability of finding the optimal features to discriminate between classes, it ignores any domain knowledge that we might already have. As such, it is potentially wasteful of the limited resources available for the project at hand.

Focusing on efficiency, instead of computing features in an ad hoc manner, they were created as follows: 1) Assumptions were made regarding the distinction between classes (e.g., households with children use more energy overall). 2) Features were created to capture this distinction (e.g., the average energy over a 4-week period). 3) Tests were performed to evaluate the validity of the assumption (e.g., visualising the feature). The tests varied in thoroughness as it was sometimes obvious from visualisation alone that they discriminated between classes. At other times, more sophisticated methods were needed, as described in Section 3.5.

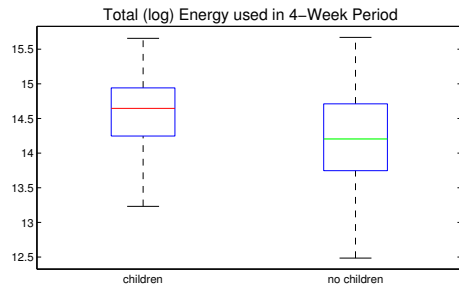
The remainder of this chapter describes features that were created from the energy reading data and justifies why it was assumed that they would discriminate between classes. The results of computing these features are then evaluated. Both classification problems (socio-economic classification and child classification) were considered when choosing features to evaluate.

Total Electricity

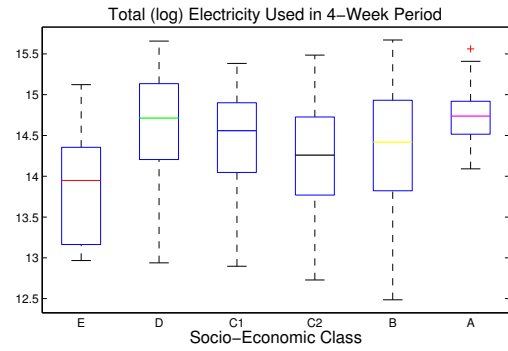
In visualising the HES data, it became evident that there were large disparities in energy usage among households. While some had an average smart meter reading of 109Wh, others averaged as little as 40Wh¹. One household was recorded to have consumed as much as 3.25kWh in 10 minutes (3,250Wh); another never used more than 198Wh over the same time interval. To determine whether these discrepancies could be attributed to different classes, the first feature that was explored was the total energy consumed within a given period of time. This was chosen to be 28 days (for reasons outlined in Section 2.2).

Building a classifier using the total electricity as input assumes that some classes use more energy than others. This can be justified as correlations between a household's disposable income and the amount of energy it uses have been observed in previous studies [25].

¹The smart meters actually measured in units of 0.1Watt hours



(a) Total electricity used by households in a 28 day period, grouped by whether the household has children or not



(b) Total electricity used by households in a 28 day period, grouped by the IPSOS social grade of the household

Figure 3.1: Total electricity used by households over a 28-day period grouped by the presence of children (left) and socio-economic status (right).

Looking at Figure 3.1, there appears to be a distinction between classes in total electricity consumption. The left hand plot, which compares households with children against those without, indicates that those with tend to use more energy. The right-hand plot, which compares total electricity according to social grade, shows that the highest socio-economic households use more energy than those of the lowest social grade. It does not, however, discriminate well between intermediate classes.

Average Daily Usage

Having established that some classes of households do indeed use more energy than others, the average energy used by each household on each day of the week can be computed to determine the underlying cause. This sort of feature explores not just whether some classes use more electricity than others, but if the electricity consumed is dependent on the day of the week. This was computed by taking the total energy used on each day, grouping similar days together (based on which day of the week they are), and then taking the average of each group.

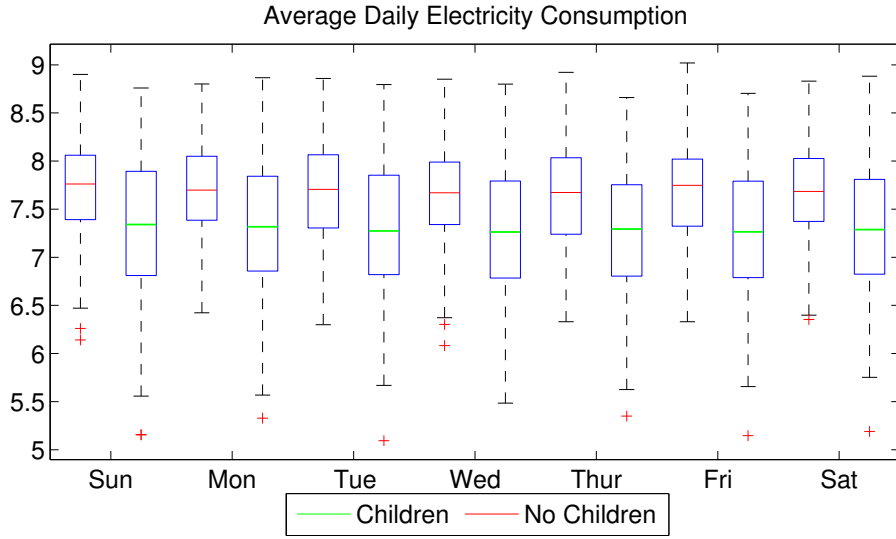


Figure 3.2: The total energy used per day, averaged over a four-week period, and grouped according to the presence of children. ‘C’ refers to households with children and ‘NC’ refers to those without children.

Figure 3.3

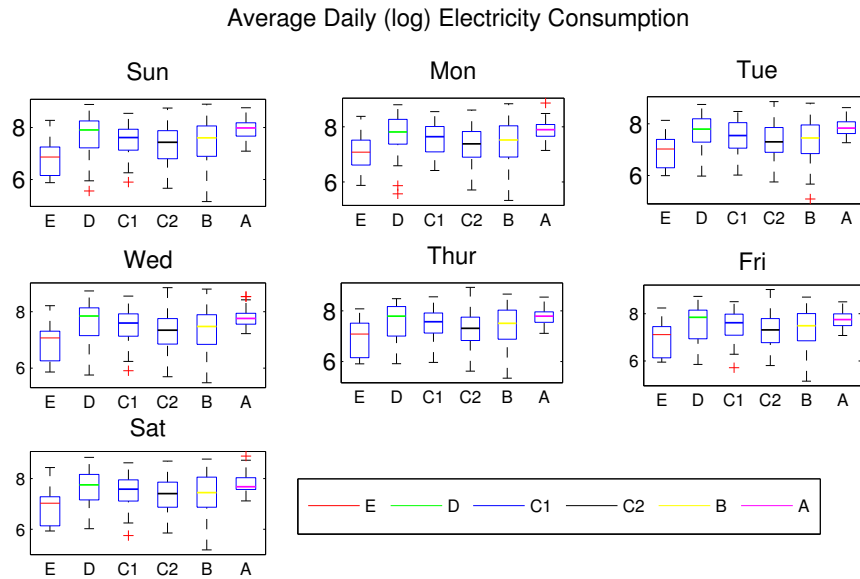


Figure 3.4: The total energy used per day, averaged over a four-week period, and grouped according to their Ipsos mori social grade

Figure 3.3 further illustrates that households with children use more power than those without. It does not, however, provide any additional insight as to when, how or why this is the case. Households with children tend to use more electricity per day, irrespective of what day of the week it is.

Similarly, Figure 3.4, which compares the average daily usage of among socio-economic groups, does not offer any new insights into the differences between classes. There is no particular day where differences in electricity consumption between classes are more visible.

It should be noted, that due to the way the data was pre-processed in Section 2.2, there is an inherent bias in features that rely on average consumption over the four-week period. If a day had to be reused in order to ensure 28 days worth of data, then it is counted twice when taking the average.

Average Part-Of-Day (APOD)

Going further, different classes potentially use more or less energy at different times of the day. For example, lower socio-economic households might use more energy during the day than those of medium or high socio-economic status. This is because the conditional probability of unemployment given lower socio-economic status is higher than that of unemployment given higher socio-economic status [26]. Similarly, it would not be unreasonable to assume that the consumption gap between households with and without children might shrink when the children are at school and widen when they are at home. APOD (Average Part-Of-Day) features are computed by grouping the smart meter readings according day-of-week (as in the previously computed feature), as well as by part-of-day. The resulting averages of each group is then taken to be a feature. As detailed below, it makes sense to look at days as the sum of four parts, resulting in 28 new features.

Most schools days in England begin at 9:00 and finish between 15:00 and 16:00 [27]. Combining this information with an assumption that as children go to bed, the activity of the other members of a household will decrease and therefore electricity consumption will drop, it is worthwhile to split each day into the following groups.

1. Morning (6:00-9:00): The time when members of the household wake up and prepare themselves for work, school etc.
2. Daytime (9:00-15:00): The time children are at school.
3. Evening (15:00-22:00): When a household can be presumed to be most active
4. Night (22:00-6:00): Depending on the type of household, the time when people might be more or less active. For example, couples without children might stay up later.

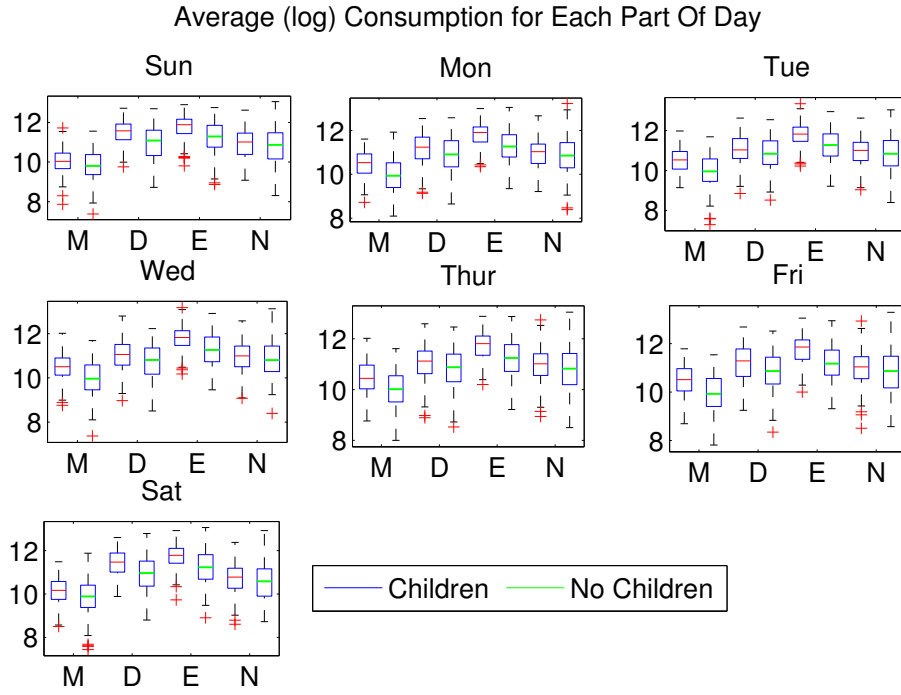


Figure 3.5

The data portrayed in Figure 3.5 indicates that energy use patterns are indeed different for households with versus without children. Much of the difference can be attributed to household activity in the Evenings (15:00-22:00). It can also be seen that on weekday Daytime (9:00-15:00, Monday-Friday), the two classes use similar amounts of electricity. However on Saturdays and Sundays, the gap widens and those with children tend to use more than those without.

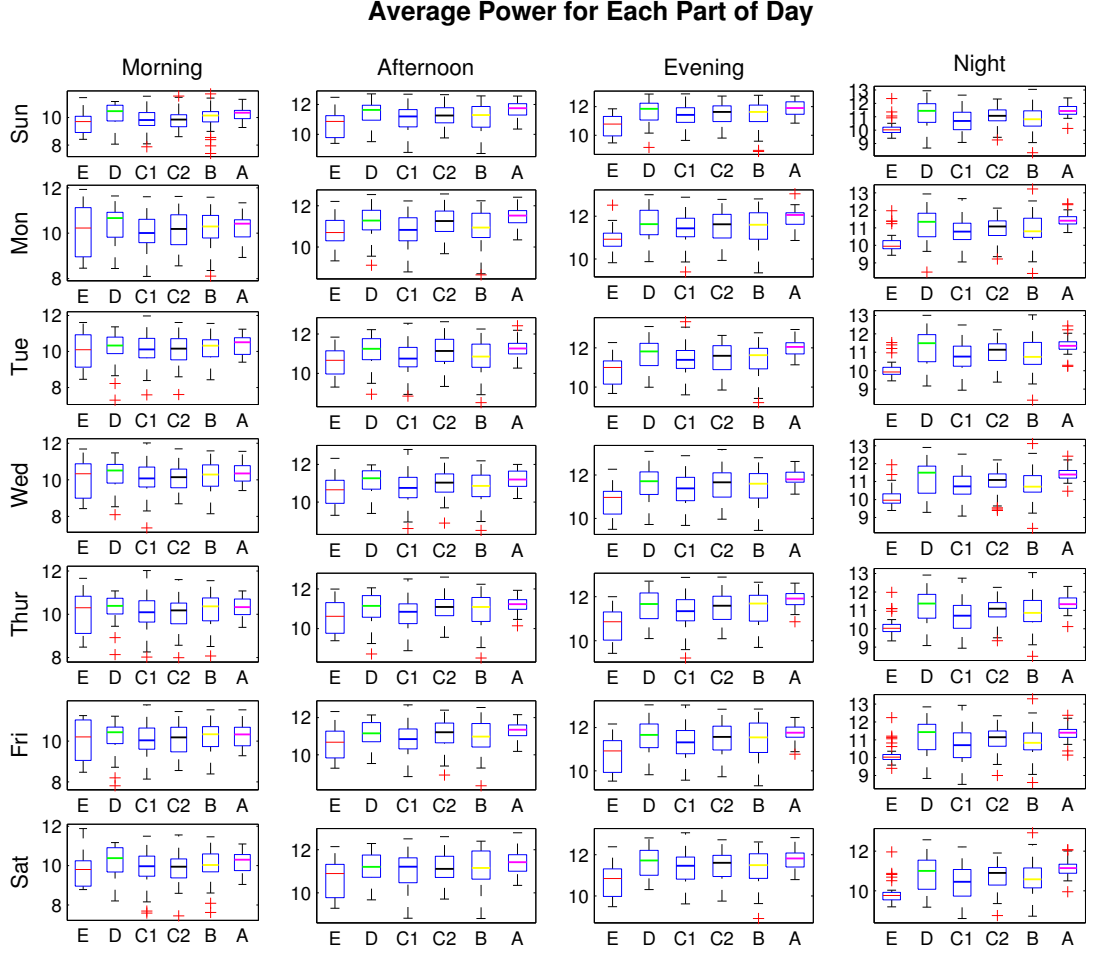


Figure 3.6

Figure 3.6, which compares socio-economic classes, shows again the same distribution as the previously computed features. Households of social grade E appear to use relatively little energy at night compared to households of other socio-economic groups, yet they seem to make up for it in the morning period, when their consumption is more akin to the other groups. Households of class A show the opposite pattern, using more energy than the others in the evenings, but normal amounts (compared to other classes) in the mornings.

Based on the observations thus far, it is likely that a classifier would have difficulty differentiating between socio-economic classes, particularly when discriminating between households of classes B or D and the rest. They have lower prior probabilities than C1 and C2, and do not look to have the extremes in energy usage that classes A and (particularly) E do.

Mean Weekday vs. Saturday and Sunday

In addition to looking at consumption features, ratios can also give insight into when a household is using its energy. Taking the ratio of the energy consumed on a weekend day to weekdays, one can determine if a household is using propor-

tionately more of its energy during the week or at the weekends. Households of social grades E, D and C2, whose chief income earners, when employed, are often either unskilled or manual labourers, or work in lower level positions within such industries as retail, hospitality and food services, are more likely to be required to work at the weekends than households of classes C1, B or A who, given their supervisory or managerial roles, are less likely to work at the weekends [28]. The feature is computed by taking the average energy consumed by a household on a Saturday and a Sunday, and dividing that by the average energy used during the week². The features can be expressed as:

$$\text{Sat Ratio} = \frac{\text{mean total energy used on Sat}}{\text{mean total energy used from Mon to Fri}} \equiv \frac{\sum_{i=1}^4 \text{Sat}_i}{\sum_{i=1}^4 \text{Mon}_i + \text{Tue}_i + \dots + \text{Fri}_i}$$

$$\text{Sun Ratio} = \frac{\text{mean total energy used on Sun}}{\text{mean total energy used from Mon to Fri}} \equiv \frac{\sum_{i=1}^4 \text{Sat}_i}{\sum_{i=1}^4 \text{Mon}_i + \text{Tue}_i + \dots + \text{Fri}_i}$$

where Day_i is the total energy used on the i^{th} occurrence of that day over the four-week period

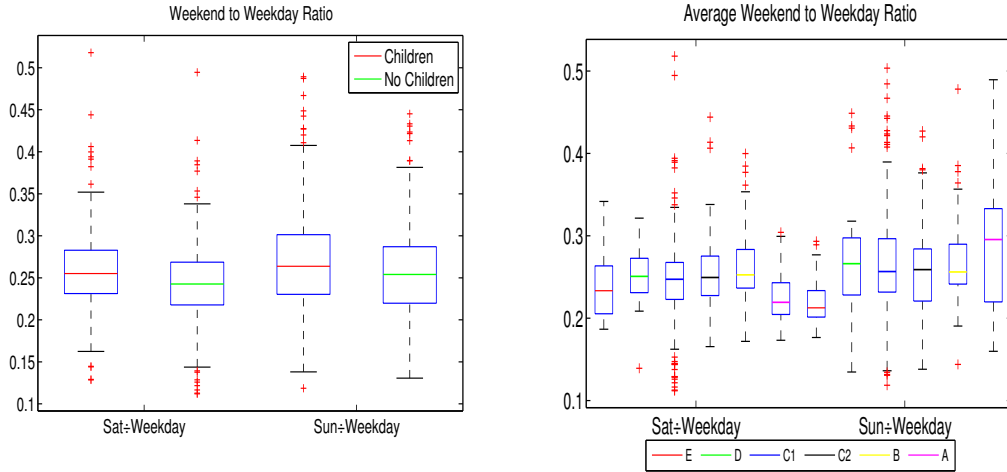


Figure 3.7: The ratio between the energy used on weekend days and the total used during the week, averaged over a four week period. This shows how the amount of energy used during the week compares to that used at the weekends.

After computing the ratio between weekend and weekday electricity consumption, classes seem to use similar proportions of their energy. And while Figure ?? suggests that households generally use more of their energy on Sundays than on Saturdays, this is independent of whether or not the household has children. Households of socio-economic class A are found to use a lower proportion of their total energy on Saturdays than other classes, but might use more on Sundays, whereas the opposite is true for households of class E. Again, there is the issue that households of classes D, C1, C2 and B are indistinguishable from one another based on the plot.

²Simply taking the total energy used on all Saturdays and Sundays and dividing it by the total used on weekdays would give the same result. However, the decision was taken to use the average because these values were conveniently available from previously computed features.

Variance on Weekdays

Thus far, the features that have been computed have been dependent on *how much* energy has been consumed. It is also worth considering what can be inferred from the volatility of a household's energy consumption over the course of a day. The assumption behind such a feature is that certain types of households will have more 'spikes' in their daily consumption. For example, households with greater disposable income (which is correlated with their socio-economic status) are more likely to own appliances that have high energy demands such as tubule driers and dishwashers.

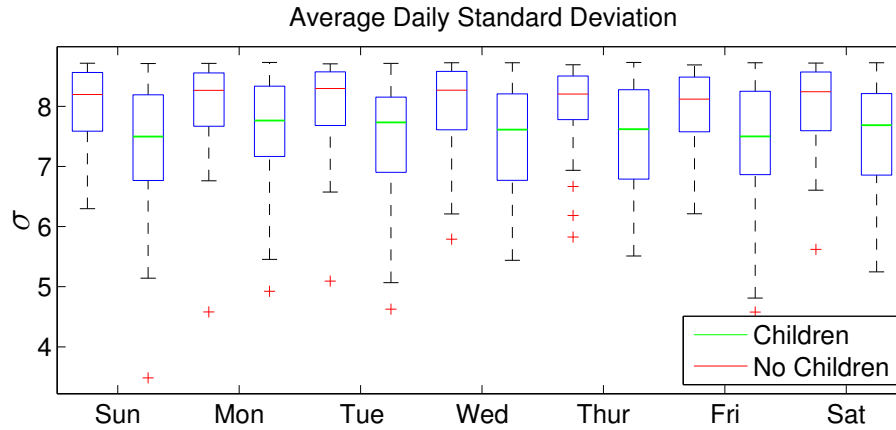


Figure 3.8: The variance of a household's daily consumption grouped by the day of the week and whether the household has children (C) or not (NC)

Although the average daily variance of households is volatile in and of itself, the results shown in Figure 3.8 indicate that the electricity use of households with children does tend to fluctuate more than those without children and therefore could be used to discriminate between households with and without children.

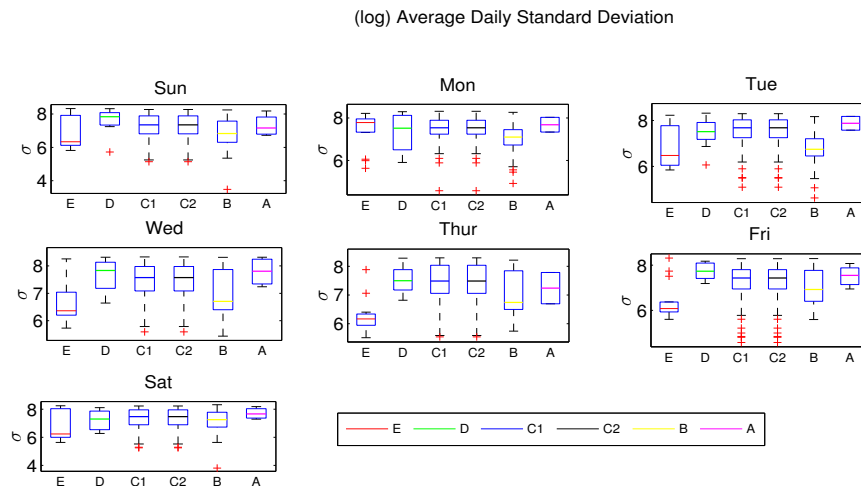


Figure 3.9: The variance of a household's daily consumption grouped by the day of the week and the Ipsos mori social grade

According to Figure 3.9, it is conceivable that the variance of a household's electricity consumption could be used to determine the socio-economic class of the household. For example, households of class E can be distinguished from the remaining classes based on the variance of their consumption on Thursdays and Fridays. On Tuesdays, households of class B stand apart from A, C2, C1 and D.

Correlation Between Weekdays

The final feature calculated from the consumption figures is the average correlation coefficient between one weekday and every other weekday. Each weekday was taken turn, and the correlation between it and each subsequent weekday was calculated. This is done for each week separately and the averaged correlation of each pair of days is considered as one feature. Rather than using the 10-minute intervals, which appeared to be too granular to capture any covariance between days, electricity readings were summed into one-hour intervals. This is done because, while people might have certain tasks that they repeat daily (such as having a cup of tea), it is unreasonable to assume that it is always done during the same 10 minute period each day, but likely to be within the same hour.

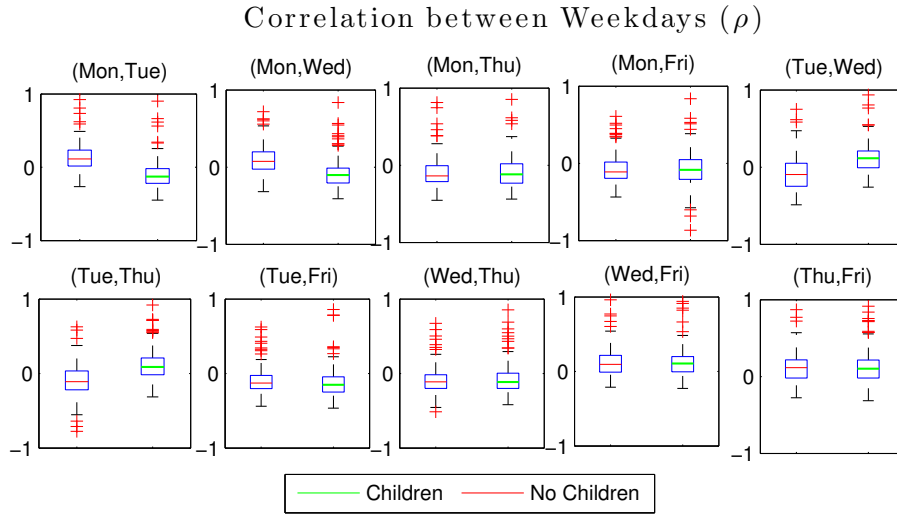


Figure 3.10: Average correlation coefficient between weekdays grouped by whether a household has children (C) or not (NC)

Looking at Figure 3.10, it appears that although the correlation coefficients are generally close to 0 (meaning there is no correlation), there are nevertheless differences between the two classes. Depending on which two days are being considered, the correlations of one class tend to be greater or smaller than that those of the others. For example, it would appear that households with children demonstrate a slightly higher correlation between their Monday and Tuesday electricity consumption patterns than those without. Whereas for socio-economic classification, as depicted in Figure 3.11, the correlation between days does not result in features that separate classes.

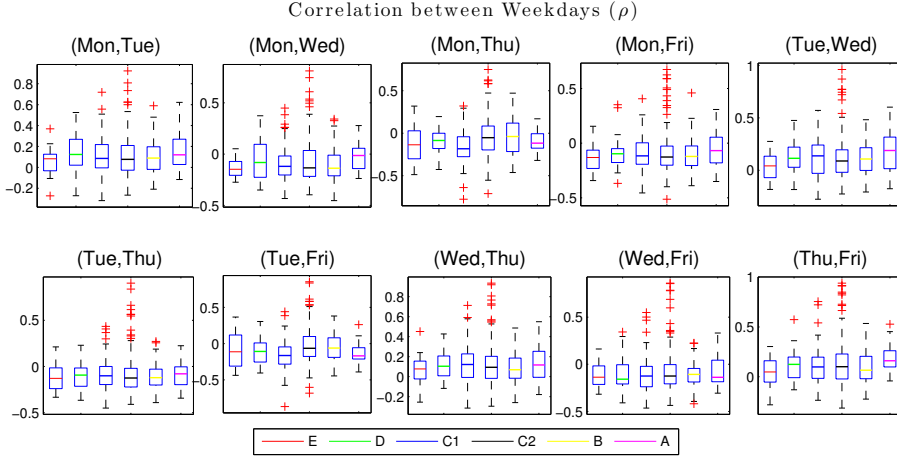


Figure 3.11: Average correlation coefficient between weekdays grouped by Ipsos social grade

3.4 Periodicity

Another approach used for feature extraction is to exploit the periodic consumption patterns exhibited by many households in order to search for temporal structures present in some classes but not in others. This method of feature extraction has been used successfully in previous studies involving forecasting and clustering. Methods outlined by Fabian Moerchen [22] for time series feature extraction are used to project each household's consumption into the frequency domain from which the most important frequencies are found. McLoughlin et al. [18] showed in their research that temporal structure is present in household electricity consumption data and can be used to characterise domestic energy demand.

Signal Smoothing

Before projecting the electricity consumption into frequency space, the Gaussian averaging operator was applied to each set of readings to filter noise whilst retaining the temporal structure of the data. Gaussian filtering (or Gaussian smoothing) is accomplished by convolving a time series with the Gaussian function. It can improve performance compared with direct averaging, as more structure is retained whilst noise is removed [29]. This is done because the time-frequency transformation used (the discrete Fourier transform method) has difficulty characterising small intervals of large electricity demand [30].

Fourier Transform

For uniform samples $[f(1) \dots, f(n)]$ of a real signal $f(x)$, the *Discrete Fourier Transform* (DFT) is the projection of a signal from the time domain into the frequency domain by

$$c_f = \frac{1}{\sqrt{n}} \sum_{t=1}^n f(t) \exp \frac{-2\pi i f t}{n}$$

where $f = 1, \dots, n$ and $i = \sqrt{-1}$. The c_f are complex numbers and represent the amplitudes and shifts of a decomposition of the signal into sinusoid functions [22].

Issues do present themselves when using this method. As already mentioned, the Fourier transform measures global frequencies and the signal is assumed to be periodic. This assumption can cause poor approximations at the borders of the time series [22].

Energy Preservation

For l time series of length m , the DFT produces an $l \times m$ matrix C of coefficients, such that element $c_{i,j}$ is the j^{th} coefficient of time series i . In our case, since the number of households, $l = 519$, is small compared to the length of each time series, $m = 4032$, the number of coefficients must be reduced in order to minimise redundancy, noise and computational time. According to Moerchen [22], the best subset of k columns is found by selecting those that optimize energy preservation E , defined as

$$E(f(t)) = \sum_{j=1}^m a_j c_j^2$$

where c_j is the j^{th} column and a_j is an appropriate scaling coefficient corresponding to signal $f(t)$.

Let I be a function measuring the importance of coefficient j on all values of l , and let $J_k(I, C)$ be a function that chooses a subset of $M = 1, \dots, m$ of the k largest values of I . Moerchen [22] proves that $J_k(\text{mean}(c_j^2), C)$ is optimal in energy preservation.

The MATLAB fast Fourier transform function (fft) was used to find the discrete Fourier transform; the five best features were chosen based on the energy preservation method.

3.5 Dimensionality Reduction

Even though the success of a classifier is dependent on several variables, which may differ from one classifier to another, all classifiers are dependent on the quality of their input data. To achieve accurate results with the least amount of computational time, it is necessary to ensure that the minimal amounts of noise and redundancy is present in the input. This may involve dimensionality reduction, the process of identifying and filtering out as much irrelevant and redundant information as possible [31].

Different classification algorithms will be affected by overparameterisation in different ways. In the K-nearest neighbour classifier, additional features can largely affect the distance between two points. While redundant features (i.e., those that don't change the distance between points) would only influence computational cost, added noise to the system can impact the distance between points, likely in a negative way.

Like K-nearest neighbour, the need for feature reduction in logistic regression has less to do with removing redundancy than with reducing noise and computational cost. Logistic regression accounts for highly correlated features by

lowering their weights. Uninformative features, however, would cause weights to be learned that do not improve the performance of the classifier.

Random forests are not as susceptible to the problem of overparameterisation as other methods. When training each tree, since the ‘best’ features will be branched on towards the top of the tree, pruning could be used to limit the size of each tree (thus avoiding overfitting). An issue would only start to arise when the number of redundant or noisy features become much larger than the number of good features. This is because, when training a tree, a random subset of features is selected as each branch is created. If the number of ‘bad’ features is much larger than the number of ‘good’ ones, then the probability of choosing a subset where no good features are present becomes significant.

Dimensionality reduction can usually be characterised as one of two tasks: *feature selection* and *feature transformation*. Feature transformation methods involve performing a transformation of the data (such as a rotation or projection) to create a new set of features (of smaller size) that has more descriptive power than the original set. A commonly used example of this is *principal component analysis* (PCA) which finds a set of orthogonal unit vectors that point in the directions of greatest variance of the data. The features are given by projecting the data onto this basis. While these sorts of methods are popular and do tend to perform well, the resulting features are usually not interpretable [32].

It might be of interest to see which features are most responsible for differences between classes. Therefore, instead of using feature transformation methods, feature selection is used to find a subset of features for which a classifier achieves its best performance. There exist numerous methods for performing feature selection, such as nested subset methods, filters or direct objective optimisation [32], as well as adaptive boosting [33].

We use *sequential floating selection* (SFS) [34] to find the optimal set of features. SFS is a greedy algorithm that works by: Starting with an empty list, sequentially considering each feature and assessing its impact on a given evaluation score. It then chooses the feature that scores best and adds it to the list. Then, it goes through each of the features that have not been added to the list, and assess their performance in combination with the features already added to the list. It find the feature that improves performance most and adds it to the list. This is repeated until the list is full [35]. A superior method, *sequential forward floating selection*, has been proven to perform better [34], which backtracks after a new feature is included to solve the *nesting* problem, it proved inefficient to implement for the multi class.

3.5.1 Implementation

Since it is not necessarily the case that the best features are the same for each classification problem, or even for each classification algorithm, the best features are found for each classifier irrespective of the others. The figure of merit for each, which is optimises the classifier is found by using cross-validation and training a classification model model with training data and then evaluating it on a validation set. If at any stage, the feature being considered improves the figure of merit, then the feature will be added to the set of ‘kept’ features.

Different evaluation scores are used depending on the classifier. In the k-

nearest neighbors classifiers, the *mincost* is, which is the predicted label with the smallest expected misclassification cost. The expectation is taken over the posterior probability, and cost as given by the Cost property of the classifier (a matrix). The loss is then the true misclassification cost averaged over the observations. For the random forest implementation, the cumulative misclassification probability of the entire ensemble is used as the cost to evaluate combination of features. In the case of logistic regression, the deviance of the fit is used. These methods were used for two reasons, firstly because efficient implementations exist with MATLAB's stats toolkit, and they produced the sets of features that performed best on when tested on a validation set.

Chapter 4

Models

4.1 Overview

There are several classification algorithms that can be used to perform supervised learning tasks and vary in their computational complexity, implementation and assumptions that they make about the distributions of the data [8]. Three well known methods are used to classify the data: Logistic regression, random forrest and k-nearest neighbour.

All three methods are examples of discriminative classifiers. The discriminative approach is appealing in that it directly models $p(y|\mathbf{x})$. Also, density estimation for the class-conditional distributions is a hard problem, particularly when \mathbf{x} is high dimensional, so if we are just interested in classification, then the generative approach may mean that we are trying to solve a harder problem than we need to [36].

4.2 Logistic Regression

For a binary classification problem $y \in \{0, 1\}$, such as discriminating between households with children ($y = 1$) and households without ($y = 0$), the logistic regression model learns a weight vector \mathbf{w} such that given some new household with feature vector \mathbf{x} , the posterior probability of that household being in class, $p(y = 1|\mathbf{x}) = g(\mathbf{x}; \mathbf{w})$ where $g(x)$ is the logistic (or sigmoid) function.

$$g(\mathbf{x}; \mathbf{w}) = \sigma(\mathbf{x}; \mathbf{w}) = \frac{1}{1 - e^{-(b+\mathbf{w} \cdot \mathbf{x})}}$$

There are numerous advantages to using logistic regression for the household classification task. Firstly, logistic regression is interpretable. After the model has been trained and the weight vectors established, they can be used to determine how important each feature is to the classifier. Secondly, the confidence of a prediction can be inferred, resulting in interpretable results. There are, however, also drawbacks to logistic regression. Since the maximum likelihood function does not have a closed form solution, an iterative process must be used instead to learn the weights, which is not guaranteed to converge.

4.2.1 Multi-class Logistic Regression

To extend the problem of logistic regression to the multi-class case, often times the *softmax* is used as a generalisation of the logistic function (σ), the predicted class of an instance is then given by

$$P(y = Y_i | \mathbf{x}) = \frac{\exp^{-(b_i + \mathbf{w}_i \cdot \mathbf{x})}}{\sum_{j=0}^J \exp^{-(b_j + \mathbf{w}_j \cdot \mathbf{x})}}$$

Although this is a valid method of classifying the data, it fails to acknowledge the ordinal property of the classes and assumes the data to be nominal. Ideally we would be able to build a model that exploits the fact that some classes are more similar than others. For example, if the true label of a household is B, then we would rather misclassify the instance as A or C1 than as D or E. Luckily, ordinal logistic regression (or ordered logit) can be used to build a model that incorporated the ordering of the classes.

McCullagh's proportional odds model [37] is a variation of a generalised linear model (glm) where the dependant variable is thought of as being continuous, but is recorded ordinally. It can be thought of as asking asking a linear model to tell you what range a dependent variable is in (as opposed to an exact value). The regression model is then given by:

$$\begin{aligned} \text{logit}(p_1) &= \log\left(\frac{p_1}{1 - p_1}\right) = b_1 + \mathbf{w} \cdot \mathbf{x} \\ \text{logit}(p_2) &= \log\left(\frac{p_1 + p_2}{1 - p_1 - p_2}\right) = b_2 + \mathbf{w} \cdot \mathbf{x} \\ &\vdots \\ \text{logit}(p_6) &= \log\left(\frac{p_1 + p_2 + p_3 + p_4 + p_5 + p_6}{1 - p_1 - p_2 - p_3 - p_4 - p_5 - p_6}\right) = b_6 + \mathbf{w} \cdot \mathbf{x} \end{aligned}$$

This model relies on the *proportional odds assumption*, which is that the \mathbf{w} s are independent of the classes (hence they have no subscripts). This translates to the assumption that the weights are the same for each cutoff, but rather the classes have different intercepts b , in contrast to multinomial logistic regression (where the dependent variables are assumed to be nominal) which learns a new set of weight parameters for each cutoff point. A further description of regression models for ordinal data in the context of machine learning is given by Herbrich et. al. [38].

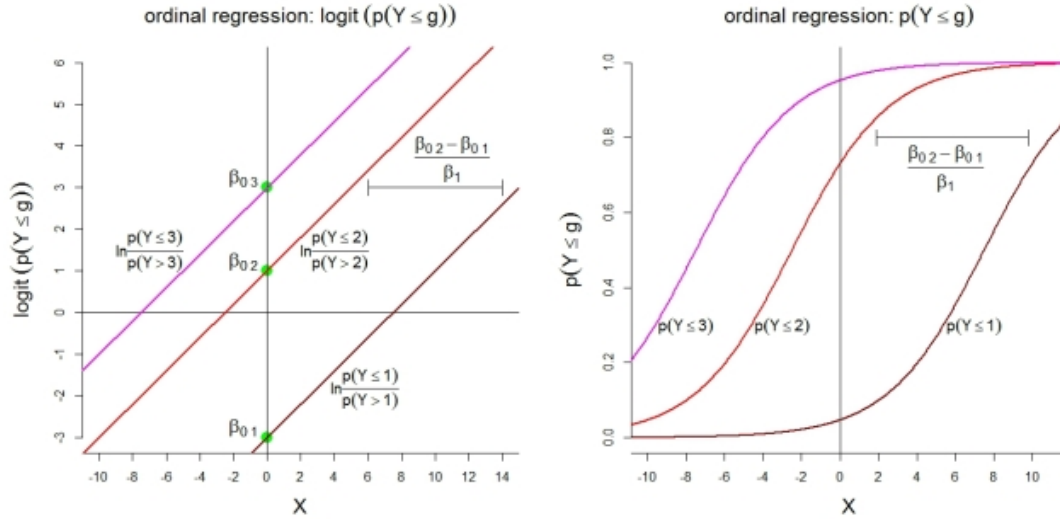


Figure 4.1: The proportional odds model assumes that the regression function for different response categories are parallel on the logit scale. Figure obtained from: <http://www.datavis.ca/courses/grcat>

4.2.2 Implementation

To build the binary logistic regression classifier, MATLAB's `fitglm` tool which fits a generalised linear model to the data. Logit link functions and a binomial distribution are passed as parameters to the `glmfit` function which produces a logistic regression model. For the case of multi-class classification, two models were created. One using McCullagh's proportional odds model (treating the data as ordinal) and one using multinomial logistic regression (treating the data as nominal). Both methods were implemented in MATLAB using the `mnrfit` tool.

4.3 Random Forest

Random Forest is a classification method that grows an ensemble of decision trees from a set of training instances and determines the class of a new instance by allowing the trees in the ensemble to vote on the most popular class. For N training sets and M features, each tree is grown by:

- Randomly sample n training instances from the N training with replacement (this will be the training sample to grow the tree).
- At each node, selecting m features at random (where $m < M$), the best of which is used to split the node.
- The trees are grown to the largest possible size (no pruning takes place).

A new instance is then classified by running it through each tree, allowing each of the trees to assign the instance a class. The predicted class of the test instance is then given by the vote of each tree.

Although (in contrast to building a single decision tree), it is not easy to visualise a random forest, it is still possible to gain an estimate of the variables

that are most important for classification and can be used on data sets with a large number of features (see Section 3.5). Random forests have been shown to perform particularly well on unseen data compared to other classification methods as they avoid overfitting by only ever looking at a random subset of features and data [39].

4.3.1 Implementation

MATLAB’s builtin `treeBagger` class was used to build the random forest. Because bootstrap aggregation is used to randomly sample the training data, the out-of-bag (oob) estimates were used to optimise the model’s parameters instead of using cross-validation. The parameters to optimise are the number of trees in the forest, and number of features m to consider for splitting each node. It was found that the, for both classification tasks, optimum number of trees in the forest is 13, and that evaluating $\frac{M}{2}$ randomly selected at each node gives the best oob error.

4.4 K-Nearest Neighbour

K-nearest neighbor is a fundamental method for classification as it is intuitive and requires little *a priori* knowledge about the data. It is a non-parametric model that classifies an unlabeled input by finding the K-nearest training points in feature space, using the classes of the nearest points to predict the class of the unlabeled point [40].

4.4.1 Implementation

MATLAB’s `fitknn` tool was used to build a nearest neighbour classification model and the optimum parameters were found using 5-fold cross-validation. The parameters to find were the distance measure, search method and k (the number of neighbours). Using the 5-nearest neighbors and euclidean distance gave the best results in cross-validation.

Chapter 5

Results

This section discusses the quantitative evaluation methods used to determine the potential for each of the classifiers to reveal household characteristics and then analyses the results from training and running each classifier.

5.1 Evaluation Methods

For each classifier, a *confusion matrix* (CM) is produced using the MATLAB tool `confusionmat`, which, for a K class classification problem, returns a $K \times K$ matrix where each element (i, j) contains the number of times an instance of class i has been classified as j . The diagonal elements of CM contain the number of instances of households that have been classified correctly for each class. [41]

The accuracy of a classifier is defined as the sum of the diagonal elements of CM, divided by the total number of samples, S .

$$ACC = \frac{\sum_{i=1}^K CM_{i,i}}{S}$$

This is compared to the accuracy of performing a random guess (RG), which assigns a household to one of the K classes at random.

$$ACC_{RG} = \frac{1}{K}$$

To account for the imbalances in classes, we also calculate the most probable class (MPC) which uses knowledge of the prior probability of each class in the training data to find a baseline by assigning all samples to the most probable class.

$$ACC_{MPC} = \frac{\text{argmax}(S^K)}{S}$$

where S^K is the number of samples from the test data that are in class K .

For socio-economic classification problem, the ordinal structure of the classes should also be taken into account i.e it is worse for our classifier to predict a household of social grade B as D, then it is to predict it as C1 or A. Therefore, the *accuracy within n* [42].

Particularly for unbalanced classes, reporting the accuracy alone is not satisfactory in determining the quality of a classifier. The obvious and well known example being; constructing a classification problem where 99% of instances are in class A and only 1% in class B. A classifier that simply predicts all new data as class A would be correct 99% of the time, but would still not be a good classifier.

A widely applied method for evaluating a classifier is to compute the *true positive rate* (TPR) and *true negative rate* (TNR). The TPR gives the proportion of positives that are correctly identified as being positive, while the TNR gives the proportion of negatives that are correctly identified as negative.

$$TPR = \frac{TP}{TP + FN} \quad TNR = \frac{TN}{TN + FP}$$

From these statistics, it is common to plot an ROC curve, which is a plot of the TPR against the *false positive rate* (FPR), which is defined as 1-TNR. The evaluation criterion (the area under the ROC curve) is preferred over the accuracy, particularly when considering unbalanced classes as the impact of skewness can be analysed [43]. To create the ROC curve, a value is found for each classifier which acts as the threshold above which an instance is classified as positive. Typically for logistic regression, this is the probability of an instance being assigned to class 1.

This is not as straight forward for random forests and knn as they are not probabilistic classifiers. Probabilities can, however be generated from the classifier results. For random forest the decision boundary may be the ratio of number of trees that vote in favor of assigning an unseen instance to class 1 and the total number of trees. In knn it is the number of nearest neighbors that are of class 1 divided by the total number of nearest neighbors.

In computing the ROC curve to evaluate the binary classification task of discriminating between households with and without children is straight forward, it is straightforward to determine which class is ‘positive’ and which is ‘negative’. However for multi-class classification it is unclear what is ‘positive’ and what is ‘negative’. When evaluating their socio-economic classifier, Beckel et. al. group nearby groups together and then use a one-versus-all approach[17, 8]. A similar method is used, analogous to the *accuracy within n* method described above, where classes within n are considered positive and all else are negative.

The final metric that is presented is the Matthews correlation coefficient (MCC) which is a value between -1 and +1 representing the correlation between the predicted and true values of a binary classifier. A MCC of -1 indicates that there is no correlation between the predicted and true class while a value of +1 would indicate a perfect classifier while a value of 0 means it is no better or worse than a random guess. MCC is a worthwhile metric to report as it gives a value to the performance without inflating the imbalances in class sizes [44].

Let X, Y each be an $S \times N$ matrix where S is the number households and N is the number classes. $X_s, n = 1$ if a sample s is predicted to be the n^{th} class and 0 otherwise, $Y_s, n = 1$ if a sample s belongs to the n^{th} class and 0 otherwise. The covariance of X and Y can then be written as

$$cov(X, Y) = \frac{1}{N} \sum_{s=1}^S \sum_{n=1}^N (X_{s,n} - \bar{X}_n)(Y_{s,n} - \bar{Y}_n)$$

where \bar{X}_n and \bar{Y}_n are the means of the n^{th} columns of X and Y respectively. The MCC is then defined as,

$$MCC = \frac{cov(X, Y)}{\sqrt{cov(X, X) \cdot cov(Y, Y)}}$$

For binary classification this can be interpreted as,

$$MCC = \frac{TP \times TN - FP \times FN}{\sqrt{(TP + FP)(TP + FN)(TN + FP)(TN + FN)}}$$

While the MCC is not commonly used when assessing binary classifiers, based on the definition of the MCC above, it can be extended to multi-class problems as described by Gorodkin[45]. If C the confusion matrix of a given classifier, then the MCC is given as,

$$MCC = \frac{\sum_{k,l,m=1}^N C_{k,k}C_{m,l} - C_{l,m}C_{k,m}}{\sqrt{\sum_{k=1}^N \left[\left(\sum_{l=1}^N C_{l,k} \right) \left(\sum_{f \neq k, g=1}^N C_{g,f} \right) \right]} \cdot \sqrt{\sum_{k=1}^N \left[\left(\sum_{l=1}^N C_{k,l} \right) \left(\sum_{f \neq k, g=1}^N C_{f,g} \right) \right]}}$$

5.2 Feature Selection

As explained in section 3.5, SFS was used to determine which features are of greatest value for each classifier. What was noticed, however, is that when running the SFS algorithm multiple times, the selected features were not always the same for each of the classifiers (even after cross-validation). This was seen particularly in random forest¹. Therefore, the feature selection algorithm was run multiple times and the features that appeared most often were used. To evaluate the feature selection method, two additional sets of features were made (one for each classification problem) by choosing features based on how they appeared to separate classes in Section 3.3 just by visualisation. All classification models are evaluated using the features found by SFS as well as the features found manually (labeled as MAN). The lists of features used for each classifier are outlined in Appendix A.

5.3 Classification Results

In this section the results of the classifiers are presented when running each model on unseen data as outlined in Section 5.1. First the results of discriminating between households with and without children is presented, then the results of the socio-economic classifiers are shown. The results are discussed to determine which classifier, and set of features, performs best on the classification tasks.

The same training and test sets are used for each classifier to ensure that the results are fair. While the training set is the same that had been used in cross-validation to optimize the classifiers, the test data was entirely unused until this point.

¹This is because random forests rely on bootstrap aggregation

5.3.1 Children vs No Children

Child vs. No Child Confusion Matrices

		SFS		MAN	
		Predicted Class			
Log Reg	Actual Classal	59	11	56	12
		6	28	15	21
Random Forest		57	13	62	8
		7	27	14	20
Knn		62	8	61	9
		10	24	16	18

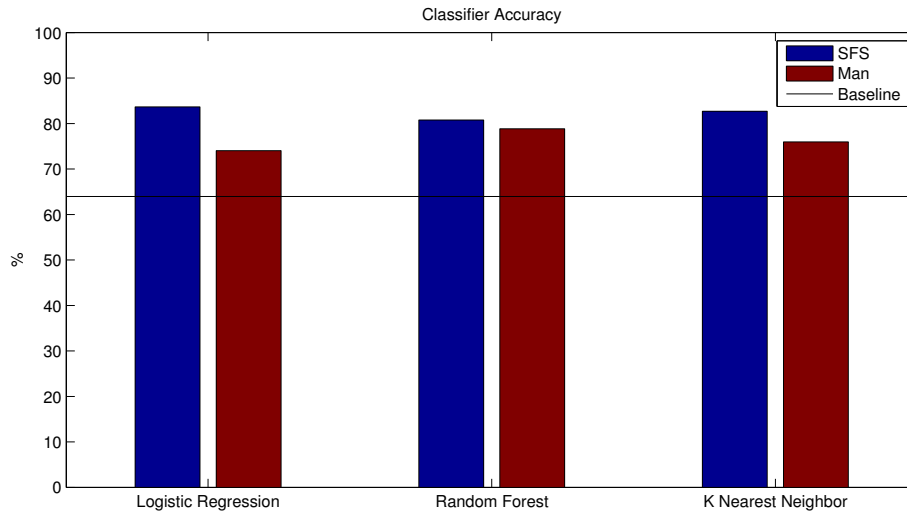


Figure 5.1: The accuracy of each classifier when used to classify unseen data defined as the number households classified correctly as a percentage of the total households in the test set. SFS classifiers are those built using features determined to be best by the sequential forward feature selection method while MAN are the features found by visually determining which features appear to best discriminate between the data

The results from Figure 5.1 show the accuracy of each classifier built to discriminate between households with and without children. All classifiers perform better than the baseline accuracy (which is the accuracy obtained all households were classified as the class with highest prior probability). The logistic regression model built with features selected using SFS predicted the greatest percentage of households correctly. Furthermore Figure 5.2 gives the Matthews correlation coefficients (MCC) of each of the classifier. As discussed in Section 5.1, the MCC is a more suitable performance measure than the accuracy as it ‘rewards’ correctly classifying the underrepresented class and ‘punishes’ that are strongly biased [8]. All classifiers take on positive values, meaning that the classifiers are less inclined to miss-classify a household regardless of which class has a higher prior probability.

While the logistic regression classifier using the SFS features classifier gave both the highest accuracy and MCC, the performance is not significantly better than the random forest and Knn methods (also using SFS). What is noticeable,

is that all classifiers performed better when trained with features found by SFS compared with manually feature selection, with the accuracy of all three classifiers that used SFS having being of above 80% and all those with manually selected features being below 80%. The distinction is even more pronounced in the MCCs of each of the classifiers, where all classifiers using SFS features have an MCC of over 0.5, while none of the ones using manually selected features do. In the case of logistic regression, there is the greatest difference in performance with the SFS classifier having an MCC of 0.64 and the MAN classifier only having an MCC of 0.42.

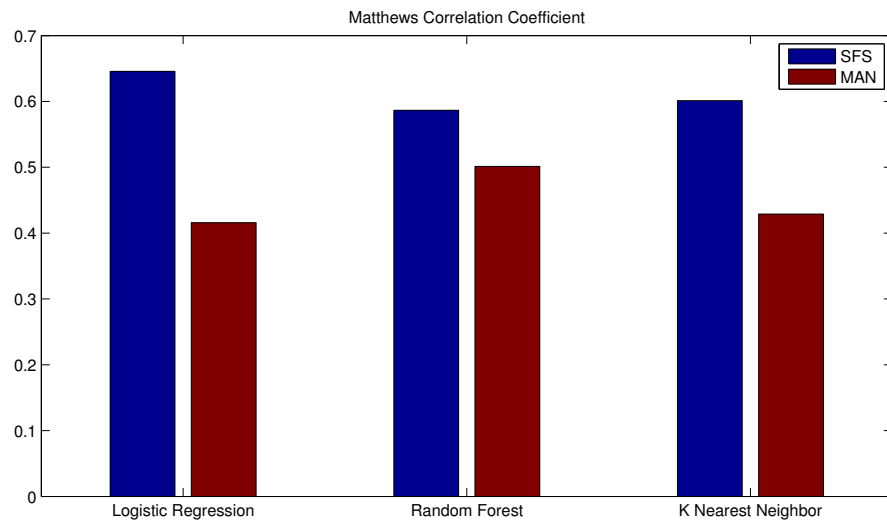


Figure 5.2: The Matthews correlation coefficient of each classifier when used to classify unseen data. SFS classifiers are those build using features determined to be best by the sequential forward feature selection method while MAN are the features found by visually determining which features appear to best discriminate between the data

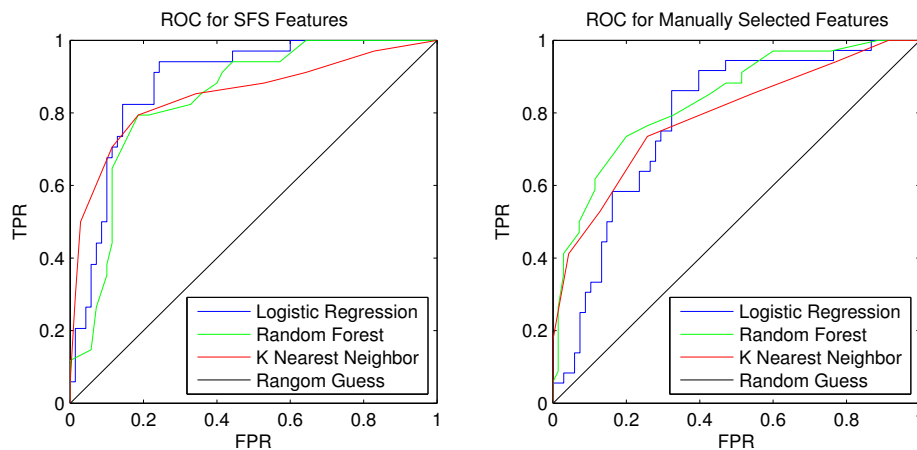


Figure 5.3: Receiver operating curve curves that show the trade-off between true positive rate and false positive rate.

The ROC curves shown in figure 5.3 shows how the TPR changes when varying the FPR. Again, it can be seen that SFS features generate better results than

MAN features. All three classifier trained on SFS features can identify 70% of households without children whilst only mislabeling 11% whereas the classifiers trained on MAN features would need to have an FPR of at least 17% to achieve the same TPR. Again, the logistic regression classifier gives the best performance (based on the area under the curve). Particularly in the Knn classifier, the TPR quickly increases with little increase in FPR, however once the specificity (1-FPR) decreases, the performance of the random forest and logistic regression classifier become more accurate than Knn.

Children vs No Children

Classifier	Accuracy (%)		MCC		ROC Area		TPR		TNR	
	SFS	MAN	SFS	MAN	SFS	MAN	SFS	MAN	SFS	MAN
Log Reg	83.6538	74.0385	0.6457	0.4159	0.8840	0.7831	0.8429	0.8235	0.8235	0.5833
Random Forest	80.7692	78.8462	0.5866	0.5012	0.8397	0.8357	0.8143	0.8857	0.7941	0.5882
KNN	82.6923	75.9615	0.6013	0.4289	0.8502	0.7905	0.8857	0.8714	0.7500	0.5294

Finally, the table above shows the TPR and TNR for each of the classifiers along with the other statistics discussed previously. While the logistic regression classifier did have the greatest accuracy and MCC, it does not have the highest TPR, meaning that it was not best at identifying positive instances (households without children) irrespective of the number of missed negatives, as opposed to the Knn classifier which was able to correctly identify 88.6% of the households without children. Looking at the TNR of each of the classifiers, Knn performs worst with both SFS and MAN features. Since it had the highest TPR, it is obvious that the classifier relies more on the prior probability. This is intuitively obvious as, if there are two clusters that overlap in feature space (i.e are not separable), and one cluster has more points, then any new point in the same space will see more neighbors of the class that occurs more frequently. From looking at the TNR, it can also be seen that the models built using MAN features rely much more on the imbalances in the sample sizes whereas models trained using SFS features are able to perform better than just a random guess.

5.3.2 Socio-Economic Group

While the results from the previous section showed that it is possible to discriminate between households with and without children, the classifiers built to determine a household's socio-economic status are not as promising. By looking at the confusion matrix generated by each classifier, as shown in Table 5.4, insight can be gained into how each of the classifiers predicts unseen data. The first thing that is noticed is that the ordinal logistic regression models are little better than a biased random guess. They predict almost all test instances as either class C1 or C2, which are the two classes with the highest prior probability based on the sample population ($p(C1) = 0.38$, $p(C2) = 0.25$). While the nominal logistic regression classifiers are not significantly more accurate, they are not as heavily biased towards the most probable classes. This indicates that the proportional odds assumption is not satisfied. This can be confirmed by looking at the weights learned in the nominal regression models shown in Appendix A. If the proportional odds assumption were upheld, then the weights across each row would be similar (other than the bias w_0)

Socio-Economic Class Confusion Matrices

		SFS						MAN					
	Actual Class	Predicted Class											
Ordinal Log Reg		1	0	4	1	0	0	0	0	2	4	0	0
		0	0	3	5	0	0	0	0	1	7	0	0
		1	0	7	18	3	0	0	0	3	26	0	0
		0	0	4	32	4	0	0	0	2	38	0	0
		0	0	3	11	1	0	0	0	1	14	0	0
Nominal Log Reg		0	0	0	6	0	0	0	0	0	6	0	0
		4	0	0	2	0	0	2	0	0	4	0	0
		1	0	1	2	3	1	1	0	0	3	4	0
		0	0	11	16	1	1	1	0	9	16	2	1
		2	1	4	29	4	0	3	1	4	31	1	0
Random Forest		2	0	1	9	2	1	0	0	0	14	1	0
		0	0	1	3	1	1	0	0	1	4	0	1
		4	0	0	2	0	0	4	0	1	1	0	0
		0	0	1	2	5	0	0	1	1	4	2	0
		0	1	18	9	1	0	0	1	20	7	2	0
Knn		1	1	5	26	5	2	2	1	6	25	4	4
		0	0	1	7	6	1	1	0	3	6	4	1
		0	0	1	3	2	0	0	0	3	1	1	1
		4	0	0	1	1	0	3	0	2	1	0	0
		0	1	1	4	2	0	1	1	0	2	4	0
		0	1	16	9	1	2	1	0	20	6	2	0
	2	1	8	24	5	0	1	2	6	28	2	1	
	1	0	2	9	3	0	1	0	0	7	7	0	
	0	0	1	3	2	0	0	0	3	0	2	1	

Figure 5.4: Each confusion matrix shows the number of households that were classified as a given class, compared to their true class. Each row represents the true label of an instance while the columns represent the predicted label, i.e element (i, j) represents the number of households that were classified as j but who's true class is i . The rows and columns go in order of increasing social grade, so the 1st row/column represents class E, the second represents class D ect.

From the confusion matrices it can also be seen that all of the classifiers give a very low probability of a household being in class D. This is not uprisng as the figures outlined in Chapter 3 suggested that it is difficult to distinguish between households of socio-ecomic classes D,C1 and C2, and since D has a much lower prior probability that the other two, a probabilistic classifier is likely to assign an unseen instance to either class C1 or C2.

Looking at Figure 5.3.2, it can be seen that, although the accuracy of the classifiers starts to quickly increase as more of its neighbors are considered positive, the benchmark accuracy also increases rapidly. This is because the most probable classes are in the middle of the ordering and are therefore more likely to be a neighboring class.

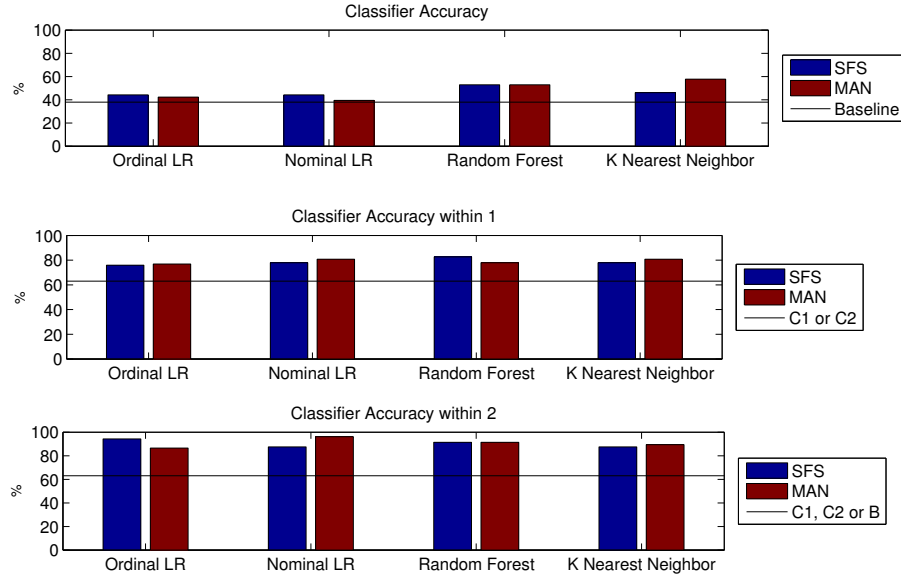


Figure 5.5: The accuracy of each of a classifier is given by the sum of the diagonal elements of its confusion matrix. The accuracy with n is the sum of the diagonal elements in addition to the elements up to n columns to the left and right of the diagonal.

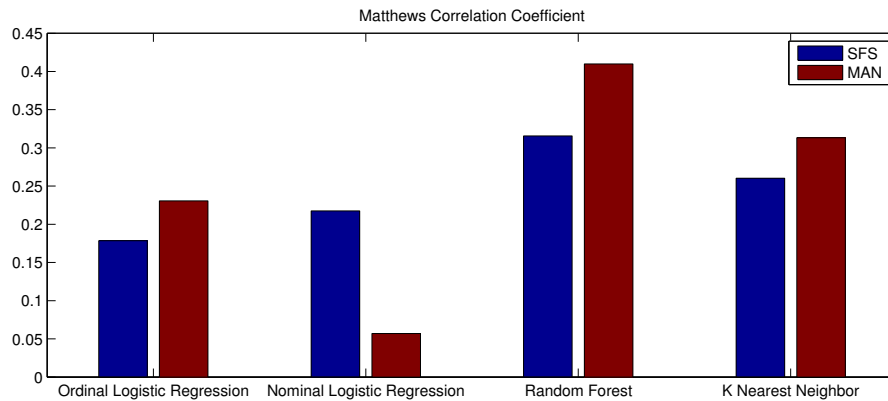


Figure 5.6: The Matthews correlation coefficient of each classifier when used to classify unseen data. SFS classifiers are those build using features determined to be best by the sequential forward feature selection method while MAN are the features found by visually determining which features appear to best discriminate between the data

Figure 5.6 shows the MMCs of each classifier. MAN features tend to do better than SFS. This could likely be because SFS is a greedy algorithm and, particularly for multi-class problems with limited amounts of data to perform validation on, a backwards step such as that used in SFFS could render a more optimal set of features. Random forests are less effected by this as they, in a sense perform as they determine which feature is best at each stage of being built. The MCC treats the data as nominal and penalizes all miss-classification equally. A modification to the MCC that accounts for the ordering of the data would give

a better evaluation of each of the models, however no such method was found in the literature.

The final evaluation metrics computed are ROC curves generated by the classifiers, shown in Appendix A, and confirm that the classifiers' performance is only useful when trying to extract households of the classes C1 and C2.

Chapter 6

Discussion

In this chapter, the important results from Chapter 3 are discussed and summarized and we try to draw conclusions about the household classification problem.

There are several major discussion points that could be outlined on the basis of the evaluation of the experimental design and so this chapter is split into 3 sections:

- Features and feature selection
- Classifiers
- Comparison to related work

6.1 Features

A large proportion of the time spent on this project was dedicated to gaining an understanding of the dataset and constructing a set of features that provide reliable results. The goal was to have a set of features that capture as much of the variance of the data in as low of a dimensionality as possible whilst still remaining interpretable. Given that one of the two classification problems was accomplished with high accuracy and relatively low error, we can conclude that such a set of features does exist. Below are some of the key observations and questions regarding feature extraction and selection .

1. *Time-frequency transformation does not capture the periodic structure of the data*

Despite numerous attempts to extract informative frequency amplitudes from time-series, no feature was found that was able to distinguish between classes of households. Various time intervals were considered, including 4-week periods, and each week and day separately. Amplitudes were also found using time-series where the weekend period had been removed to see if patterns emerged over working days but were disrupted by weekends. The result was that, although taking the fft identified periods in the energy use of households, these could not be attributed to any one class relative to the others.

2. *Sequential forward selection provides a better method of selecting features than manually searching for a set, for finding households with children but not to determining socio-economic class*

In the problem of discriminating between households with and without children, the classifiers that relied on features selected by SFS performed better than the features selected by hand on almost all accounts. The performance metric with the largest gap was the *true negative rate*. Classifiers using SFS features had, on average, 28% better results than those. In the socio-economic classification problem, it is argued that SFS performed worse than choosing features based on human intuition. While the accuracies are comparable, the MCCs' are lower for most of the classifiers built on SFS features. One explanation for this is that the sample sizes of each class are small, and more data would allow the models determine the best features with more confidence. Another explanation is that, because SFS is a greedy algorithm, it is subjective to the 'nesting effect', that once a feature has been added it can't be removed [32].

Which features are selected by SFS is dependent on what cost function is used to penalise the classifiers. Numerous cost functions were tried for each of the classifiers including misclassification rate, mean absolute error and false positive rate. When testing on the validation set, it was found that using more holistic cost functions gave better performance. A holistic being one that gives not solely based on the number of misclassified points.

3. *The optimum set of features is different for each classifier, even when tackling the the same classification problem*

Cross-validation was implemented such that the training set was randomly split into five sets each time a classifier was trained (with each class represented proportionately the same in each set). This resulted in, especially for the inferring socio-economic group, the SFS method learning a new set of 'best' parameters each time SFS was run. This can be attributed to the limited sample size. A larger set of data would give more stability in the results. The exception to this being the random forest which relies on random selection of features when learning each branch. It can therefore be argued that it was redundant to implement additional feature selection methods in the random forest classifiers.

6.2 Classifiers

While the majority of the time was spent understanding the data and extracting features, the classifiers play a crucial role in the outcome of the project. The three classifiers, logistic regression, random forest and Knn are discussed and their implementation critically evaluated.

6.2.1 Logistic Regression

1. *Outperforms random forest and Knn in discriminating between households with and without children*

With the greatest area under the ROC curve, along with highest accuracy and MCC, the logistic regression classifier is concluded to be the best-performing model for this specific binary classification model. While Knn was able to better identify the childless households, it fell short in identifying the households with children. The logistic regression model did a better job at identifying households that have children present.

It is possible that the underlying reason for the positive results is that households with children will tend to have more occupants, which is directly correlated to the amount of energy consumed by the household. However, after testing the correlation between the misclassified and the number of occupants of a household, no correlation was found.

2. *Both ordinal regression and multinomial logistic regression underperform relative to random forest and Knn in socio-economic classification problem*

Despite being the only model that takes the ordered nature of socio-economic classes into account, the proportional odds model ultimately performed no better than a biased random guess, assigning households to either C1 or C2. While previous studies have shown links between the amount of energy consumed and disposable income (which is itself linked to the socio-economic class), analysis of the HES data as well as other studies on domestic energy consumption found that not just lifestyle, but also dwelling-specific factors contributed to the electricity consumption of households. This is suggestive that, while it is possible to infer a households socio-economic status, more sophisticated methods need to be used to account for these factors.

6.2.2 Random Forest

1. *Improved performance not guaranteed using SFS*

Indicated by the results of the multi-class problem, employing statistical methods to reduce the dimensionality of the features used by the random forest classifier don't give better results on test data.

6.2.3 Knn

1. *The larger K is, the more skewed the tradeoff between TPR and FPR becomes*

During the optimisation phase, the number of nearest neighbors was adjusted to find the optimum value. As K was increased, the accuracy and TPR continued to increase whereas the TNR declined until performance was equivalent to a biased guess. This is due to the imbalances in class sizes and can be adjusted for by limiting the size of K . Conversely, using small values of K such as 1 or 2 also produced poor results because the classes are not separable. Using the 5 nearest neighbors to evaluate the class of a new point gave the best results during cross-validation.

2. *Euclidean distance gives the most reliable results*

MATLAB’s builtin Knn predictor allows numerous different distance measures to be specified including euclidean, Hamming, Manhattan and Mahalanobis. Of these, euclidean distance was found to give the most best results based on TPR and TNR tradeoff. Euclidean distance assumes that each dimension is equally weighted which is reasonable since feature selection methods were used to determine a subset of features that reduce noise.

6.3 Comparison to Previous work

Comparing the results obtained here to those found by Beckel et al. [16, 17, 8] who used smart meter data from Irish households to predict the socio-economic class and presence or absence of children, the classifiers produced here perform better. While Beckel et al. were able to construct an SVM classifier that had an accuracy of 71% and MCC of 0.32 in discriminating between households with and without children, the results here showed that it is possible to obtain an accuracy of 83.7% and MCC of 0.64 using logistic regression — a notable improvement. While Beckel et al. achieved similar accuracy in their attempt to predict socio-economic class, the maximum MCC they obtained was 0.19, whereas the random forest constructed here had an MCC of 0.4. While this is not a strong correlation, it does indicate stronger predictive power than previous attempts.

Chapter 7

Conclusion

The goal of this project was to address the privacy concerns raised regarding smart meter data by constructing models to infer household properties. We have been able to confirm that, although there are likely numerous factors that determine the way in which a household uses energy, it is possible to extract meaningful information about the occupants from smart meter data. The main contributions of this project are:

- Dataset: Data pertaining to the electricity consumed by households that participated in the HES study was extracted and inserted into a MySQL database. This raw data was manipulated to construct a dataset of 519 labeled time-series electricity consumption data, each of which of uniform length and granularity.
- Feature Engineering:
- Classification

The results from Chapter 5 give valuable insight into what sorts of information can be inferred about a household from their electricity consumption. The amount of electricity used in a home is dependent on numerous factors concerning the lifestyle of the occupants, as well as properties of the dwelling itself, and while the automatic classifiers presented here . While the average consumer may be put somewhat at ease that it was not possible to infer a household's socio-economic status with confidence, the results presented here have shown that intimate information about a household can be inferred by electricity consumption data gathered by smart meters.

There were very few trends linking energy labels and socio-economic group

A challenge in applying these methods in practice would be in collecting reliable data. While energy companies will have access to much more smart meter data than that present in the HES study, obtaining labels for the data would be a challenge.

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Appendix A

Children

SFS			Manual
Log Reg	KNN	Rand Forest	
Mon Daytime	Mon Evening	Thur Total	Month Total
Tue Evening	Mon Night	Sun Night	Sun Daytime
Wed Night	Wed Evening	Mon Morning	Sat Evening
Thur Daytime	Fri Morning	Mon Daytime	Thurs Variance
Fri Morning	Sat/Weekday Ratio	Mon Evening	Mon Morning
Tue Variance	Sun Variance	Tue Daytime	Fri Evening
Thur Variance	Mon Variance	Fri Night	Sat Variance
Sat Variance	$\rho(\text{Mon Thur})$	Thur Variance	Mon Total
$\rho(\text{Mon Tue})$	$\rho(\text{Mon Fri})$	Fri Variance	Sat Total
$\rho(\text{Wed Thur})$	$\rho(\text{Tue Wed})$	$\rho(\text{Mon Wed})$	$\rho(\text{Mon Tue})$

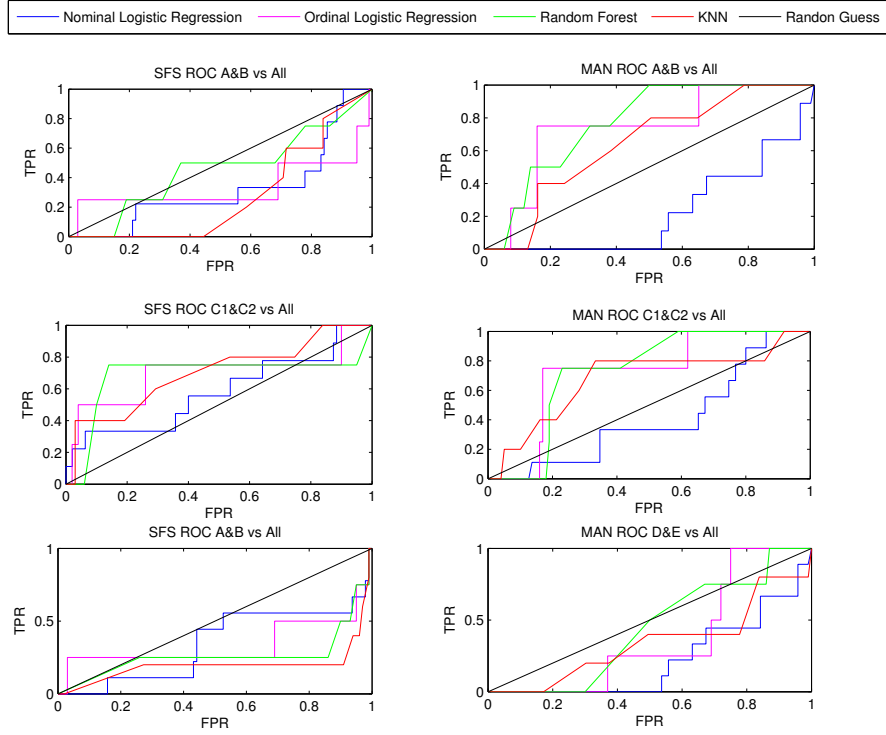
Table A.1

Social Grade

SFS				Manual
Ord Log Reg	Nom Log Reg	KNN	Rand Forest	
Mon Morning	Fri Total	Fri Total	Sun Total	Mon Night
Tue Morning	Mon Morning	Tue Morning	Wed Total	Tue Variance
Tue Daytime	Tue Morning	Wed Night	Mon Morning	Mon Total
Fri Night	Tue Daytime	Thur Morning	Mon Night	Tue day
Fri Variance	Wed Morning	Fri Morning	Wed Morning	Sun Night
Sat Variance	Wed Daytime	Sat Evening	Wed Evening	Thur Night
$\rho(\text{Mon Tue})$	Wed Evening	Sun Total	Fri Night	$\rho(\text{Tue, Fri})$
$\rho(\text{Mon Fri})$	Friday Morning	Thur Variance	Thur Variance	Thur Total
$\rho(\text{Wed Fri})$	Fri Night	Fri Variance	$\rho(\text{Mon Fri})$	Sat Night
First Fourier Feature	Sat Daytime	$\rho(\text{Wed, Thur})$	First Fourier Feature	Fri Evening

Table A.2

Figure A.1: ROC curves of socio-economic classifiers



Nominal Logistic Regression Weights

	boundary 1	boundary 2	boundary 3	boundary 4	boundary 5
w_0	51.3976	19.566	43.2567	36.3944	38.2503
w_1	3.8958	2.7275	6.027	3.3391	4.5195
w_2	-2.7457	0.1167	-2.6408	-1.4902	-1.2886
w_3	4.1992	3.3548	2.9044	1.8177	2.7361
w_4	-1.7274	-2.4818	-2.6266	-3.7323	-3.3666
w_5	-0.2175	-2.7121	-1.8633	-0.0991	-1.088
w_6	3.0446	1.175	2.9184	1.8555	1.4066
w_7	-2.2498	-0.8725	-3.4686	-2.1848	-2.873
w_8	-4.0052	-1.4543	-2.2931	-1.7864	-2.1979
w_9	-3.437	-0.5247	-1.1193	-1.2472	0.1815
w_{10}	0.0349	-0.0294	0.3932	1.6358	0.2633