MS-E2177 Seminar on Case Studies in Operations Research

Final report: Disaggregation of electricity data

Client: Fortum

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Abbreviations

ARS	Adaptive Rejection Sampling
CFHMM	Conditional Factorial Hidden Markov Model
CFHSMM	Conditional Factorial Hidden Semi-Markov Model
CO	Combinatorial Optimization
FFBS	Forward-Filtering Backward-Sampling
FHMM	Factorial Hidden Markov Model
FHSMM	Factorial Hidden Semi-Markov Model
HMM	Hidden Markov Model
IBP	Indian Buffet Process
MIBP	Markov Indian Buffet Process
NFHMM	Nonparametric Factorial Hidden Markov Model
NILM	Non-Intrusive Load Monitoring
NILMTK	Non-intrusive Load Monitoring Toolkit
REDD	Reference Energy Disaggregation Data Set

1. Introduction

1.1 Background

Electricity disaggregation, or Non-Intrusive Load Monitoring (NILM), is the process of separating the total electrical load of a single household into appliance specific loads. It is used as an alternative to the intrusive monitoring of each appliance via individual device load meters, which can be expensive for energy companies to deploy on a large scale. Electricity disaggregation methods together with the increasing number of available household smart meters have the potential to allow energy companies to gain insights into customer electricity usage behaviour.

Fortum is a Finnish leading clean energy company which provides its customers with electricity, heating and cooling as well as smart solutions. Fortum operates in both energy generation and sales in the Nordic and Baltic countries, Russia, Poland and India. It has access to vast amounts of energy consumption data and is interested in evaluating whether these datasets could be used to build new products and services. Specifically, Fortum is interested in understanding the possibilities and limitations of currently available power disaggregation technologies.

1.2 Objectives

In this project, our high-level objective is to study electricity disaggregation methods, seeking to help Fortum understand the possibilities and limitations of currently available electricity disaggregation technologies. Additionally, we develop and implement a proof of concept electricity disaggregation model seeking to test and demonstrate how Fortum could utilize their own consumption data.

2. Literature review

Electricity disaggregation was proposed by George Hart in the late 1980s and has been an active area of research since the 1990s (Hart, 1992). Hart's work focused on detecting individual appliances based on the changes in the aggregate electricity consumption signal. In these so-called event-based methods, events are first detected and then classified based on the transient event characteristics. Based on classification, the events are assigned to different devices by keeping track of their operation. Expanding on Hart's work, algorithms using more advanced event classification methods such as neural networks and Support Vector Machines, have been explored (Roos et al., 1994; Farinaccio and Zmeureanu, 1999; Onoda et al., 2002).

Approaches that utilize high frequency electricity consumption data with sampling rates from tens of Hz up to several MHz have been also explored (Prudenzi, 2002). In these methods, the household consumption is disaggregated into individual appliances based on the different orders of harmonics present in the electrical noise of the household electricity consumption. High sampling frequency methods allow for higher disaggregation precision and are able to identify more distinct appliances than methods based on low sampling frequency data (Armel, 2011). However, the main drawback of such disaggregation methods is the high cost and installation effort of the electrical sensors providing the data.

Recently, there has been increasing interest in model-based methods that move away from the standard event-based framework (Kim et al., 2011; Kolter and Jaakkola, 2012; Parson et al., 2011). These model-based methods refer to a family of methods which maintain an explicit representation of the entire system state, instead of modelling individual events. The underlying assumption of these models is that the electrical signal is the output of a stochastic system. Particularly, with the increasing number of available smart meter data, model-based methods that utilize low frequency electricity consumption data in the range of 1 Hz or lower have attracted the interest of researchers (Kim et al., 2011). A useful framework for model-based low frequency disaggregation is Factorial Hidden Markov Models (FHMM), in which each household's electricity consumption is modelled as a parallel Markov chain evolving independently in time.

In the following sections, we review some of the more promising methods that have been used in electricity disaggregation in recent publications. Additionally, we introduce a fundamental classification of disaggregation methods based on the requirements of the available training data for each method: supervised and unsupervised methods. Lastly, we describe why and how an open source energy disaggregation toolkit was needed and developed to speed up progress of energy disaggregation research.

2.1 Supervised and unsupervised methods

Disaggregation methods can be classified based on the type of data used in the disaggregation algorithm. All disaggregation methods take an aggregated electricity signal as input with the aim of decomposing, or disaggregating, the input signal into individual appliances' signals as accurately as possible. However, the way the model parameters are obtained differ between disaggregation methods.

Supervised disaggregation methods require the labelled ground truth data to determine the model parameters and to disaggregate new aggregated signals. This ground truth training data can be obtained by installing sensors and monitoring each appliance separately. Supervised learning methods usually require the training data for each household separately in order to work well. The drawback is that such training data can be expensive or difficult to obtain (Zoha et al., 2012).

Because of the limitations of supervised methods, there has been interest in unsupervised approaches in recent years (Kim et al., 2011; Parson et al., 2014; Jia et al., 2015; Zhao et al., 2016). Unlike supervised learning, unsupervised learning does not require appliance-level training data from households. In its most pure form, unsupervised learning does not require any prior knowledge of appliances in the household, and in some cases not even the number of appliances is known (Jia et al., 2015). Consequently, methods that utilize unsupervised learning are not able to assign labels to each disaggregated appliance, because there is no prior information about the names of appliances. Therefore, some labelling process is required to join the disaggregated data and the names of the appliances together.

2.1.1 Supervised electricity disaggregation

This section describes different fully and semi-supervised approaches for the energy disaggregation problem proposed in the literature. Zoha et al. (2012) divides supervised approaches into two categories: optimization and pattern recognition based methods.

Optimization based methods compare the feature vector of an unknown load to feature vectors of known loads stored in a database and then attempt to minimize the error between them. There are several approaches to the optimization problem, such as integer programming (Suzuki et al., 2008) and genetic algorithms (Baranski and Voss, 2004). One optimization approach implemented in the Non-Intrusive Load Monitoring Toolkit (NILMTK) is combinatorial optimization which is discussed in the following chapter.

Pattern recognition methods contain several different approaches ranging from Artificial Neural Networks (ANN) and Hidden Markov Models (HMM) to Support Vector Machines (SVM) and Bayesian approaches. For example, small neural networks have been applied on NILM since the mid 90s when Roos et al. (1994) introduced a NILM method that analyses the load current and voltage in detail. A more recent method introduces an ANN approach that can recognize appliances in real-time provided that training is done for every appliance (Ruzzelli et al. 2010). Altrabasi et al. (2016) developed a low-complexity supervised method using k-means clustering and SVM to disaggregate low-sampling rate data. The FHMM approach implemented in NILMTK belongs to this category and the method will be described in more detail the following chapter.

An alternative approach to fully supervised methods involves manipulating the aggregated smart-meter data so that the load signatures of appliances can be detected separately. This is enabled by turning on each appliance sequentially while keeping others turned off. Such an approach is often called semi-supervised, because the installation and use of device-specific sensors is avoided. Alternatively, researchers have studied semi-supervised models which can utilize existing labelled appliance datasets to process the aggregate signal, but the results are not comparable to methods using household specific datasets. One such example is discussed by Parson et al. (2004) in which a semi-supervised approach is used for the disaggregation of household electricity consumption. Parson et al. use a supervised learning method for an existing labeled appliance specific dataset, which in turn is tuned by an unsupervised learning method over the aggregate data. Thus, the household specific appliance level measurements are avoided.

2.1.2 Unsupervised electricity disaggregation

In this section, we describe unsupervised electricity disaggregation methods that have been published in the last decade. A widely used approach to model the electricity disaggregation problem is the Hidden Markov Model (HMM). In HMMs, a Markov chain with hidden states evolves in time according to its state transition probabilities. The hidden states cannot be observed directly, but the states generate observations that depend on the state via emission probabilities. An extension of HMMs, Factorial Hidden Markov Models (FHMM), model each appliance as a parallel HMM (Ghahramani and Jordan, 1997). Each HMM emits an output and the observed aggregate signal is a function of these outputs. In additive FHMMs the observation is the sum of the outputs of HMMs.

There are several different variants of FHMMs in the literature. Kolter and Jaakkola (2012) developed a convex quadratic programming relaxation of the inference problem by assuming that appliances do not change state simultaneously. Kim et al. (2011) explore and evaluate the performance of four HMM variants: FHMM, Factorial Hidden semi-Markov Model (FHSMM), Conditional Factorial Hidden Markov Model (CFHMM) and combination of FHSMM and CFHMM, CFHSMM. CFHMM extends FHMM to include additional features, such as time of day and appliance dependencies, whereas FHSMM extends FHMM to model the state occupancy durations in a more sophisticated way. As a combination of the previous two methods, CFHSMM outperforms the other three methods in the paper. Johnson and Willsky (2013) introduce explicit-duration Hierarchical Dirichlet Process Hidden semi-Markov Model (HDP-HSMM) to utilize the advantages of Bayesian nonparametric methods and the semi-Markov property. Jia et al. (2015) represent a fully unsupervised NILM framework using Nonparametric FHMM (NFHMM). This method uses the Indian Buffet Process as a prior to resolve the problem of a possibly infinite number of appliances in FHMM.

In addition to HMM-based methods, other unsupervised approaches, such as methods based on Graph Signal Processing (GSP), Dynamic Time Warping (DTW) and Deep Learning have been developed. Zhao et al. (2016) introduce a fully unsupervised event-based GSP method which, in contrast to conventional signal processing approaches, embedded the structure of signals onto a graph. The algorithm applied adaptive thresholding, signal clustering and pattern matching for solving the disaggregation problem. Liao et al. (2014) propose an unsupervised disaggregation algorithm based on DTW for low-sampling rate data. After detecting events, DTW matches events using a nonlinear mapping of an event window to another by minimizing the distance between them via dynamic programming. Lange and Bergés (2016) develop an unsupervised Deep Learning method for high-frequency power disaggregation. Their approach identifies additive subcomponents of the aggregate signal in an unsupervised way by training a neural network. After identification, the electricity disaggregation is regarded as a non-linear filtering of the current signal.

2.2 Open source in electricity disaggregation

The problem of developing the optimal disaggregation method is not the only major problem researchers in the field of electricity disaggregation are tackling with. According to Batra et al. (2014), three additional problems impede progress in the field. The first pertains to the data used: Researchers have analyzed and developed methods usually with a single dataset which may not be comparable to the datasets used by other researchers and may not even be accessible to them. Collecting, processing and organizing data to produce datasets with suitable quality for NILM research is costly. The second problem arises when researchers try to evaluate the performance of a new disaggregation method. Access to reference implementations of previously developed methods is required in order for comparative analysis and benchmarking of new methods to be feasible. The third problem arises when researchers conduct such analysis or benchmarking or have already published the results. The exact benchmarking methods must be known and preferably identical across researchers for a straightforward comparison of different studies.

These three major problems inspired a team of researchers to develop an open source toolkit to help address these challenges. Consequently, Batra et al. (2014) published the Non-intrusive Load Monitoring Toolkit (NILMTK). The toolkit was designed specifically to lower the barrier for researchers to implement new disaggregation algorithms and facilitate the comparative analysis of different algorithms across diverse data sets. The toolkit was released under the Apache 2.0 licence allowing anyone to use and extend the toolkit for any purpose. This drastically lowers the need for researchers to reinvent the wheel when faced with one or more of the aforementioned problems. Since the toolkit was published in GitHub, it has been forked 117 times, although the rate of further development of the toolkit has diminished.

The toolkit is essentially a collection of Python modules designed to be utilized by scripts or interactively via iPython notebooks. The modules include parsers for a range of public datasets such as REDD (Kolter and Johnson, 2011) as well as a collection of functions for the preprocessing and statistical description of the data. The modules also include a number of reference benchmark disaggregation algorithms as well as functions for computing disaggregation accuracy metrics. Python was chosen because it offers a vast set of libraries supporting both machine learning research and the deployment of such research as web applications. The toolkit requires that datasets are described with rich metadata which conforms to the NILM Metadata specification. These datasets are then converted to the HDF5 format for more effective use. Some effort has also been put into enabling the convenient use of the toolkit even when the datasets are very large.

However, the toolkit is still at an early stage in which it is useful merely for researchers. It cannot perform any out-of-the-box disaggregation without submetered data. That is because the set of reference disaggregation algorithm implementations include only supervised algorithms. However, the unsupervised NFHMM algorithm developed in this research project is already a major step toward extending the toolkit.

The first notable benchmark algorithm implemented in NILMTK is combinatorial optimization (CO). In essence, during the training period the model learns the total number of appliances and the consumption levels of each appliance. During disaggregation it then tries to solve the optimization problem of minimizing the difference between the sum of predicted appliance states and observed aggregate with respect to the appliance levels.

The second notable benchmark algorithm implemented in NILMTK is a one dimensional factorial hidden Markov model (FHMM). During training the algorithm constructs an independent Markov chain for each appliance. Then in disaggregation it uses these parallel Markov models and exact inference to find the most likely state combination. The next chapter describes the FHMM in more detail.

More information on NILMTK and some iPython notebooks that demonstrate how NILMTK can be used are available in the original publication by Batra et al. (2014).

3. Theory

3.1 Hidden Markov Models

Hidden Markov models (HMM) are widely used in modeling discrete time series data. The HMM models the system as a hidden Markov chain, $Z_1, \dots, Z_T$, with each Z_t having N possible states. The hidden Markov chain evolves over time according to a $N \times N$ state transition matrix $\mathbf{W}$. The states of the Markov chain cannot be observed directly, but at each time step t the hidden chain generates observation Y_t from a likelihood model F that is parametrized by a state dependent parameter θ_{Z_t}. Figure 3.1 illustrates the HMM as a graphical model. Using the previous assumptions, we can now determine a probability distribution over observations Y_t, $t = 1, \dots, T$, by $p(Y_1, ..., Y_T, Z_1, ..., Z_T) = \prod_{t=1}^{T} p(Z_t|Z_{t-1})p(Y_t|Z_t) = \prod_{t=1}^{T} W_{Z_t,Z_{t-1}} F(Y_t; \theta_{Z_t})$, where $W_{Z_t,Z_{t-1}}$ is the element of the state transition matrix $\mathbf{W}$ corresponding to the transition $Z_{t-1} \to Z_t$

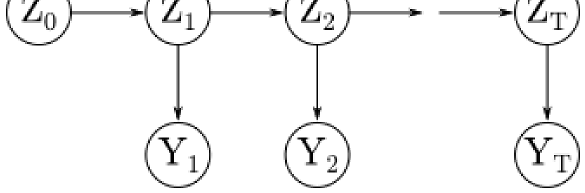

Figure 3.1. The graphical model of the Hidden Markov Model.

3.2 Factorial Hidden Markov Models

The HMM is not the most effective way to model appliances in a household: the hidden Markov chain would need to take every combination of the states of appliances as states, which would lead into an extremely large transition matrix $\mathbf{W}$.

Instead, the hidden states can be represented in a factored form. The FHMM models the system as K parallel hidden Markov chains $Z_1^{(k)}, ..., Z_T^{(k)}$, $k = 1, ..., K$, where each chain generates an output at time step t using some state dependent likelihood model. The observation Y_t is then a function of these outputs (Ghahramani and Jordan, 1997). The graphical model of FHMM is shown in figure 3.2. In the case of electricity disaggregation, the natural choice is additive FHMM, i.e. the observation Y_t is the sum of the outputs of each chain at time step t. Each of the markov chains evolves independently according to its state transition matrix $\mathbf{W}^{(k)}$, and each chain (appliance) is assumed to operate between only two states, either ON or OFF, leading to K 2×2 state transition matrices $\mathbf{W}^{(k)}$.

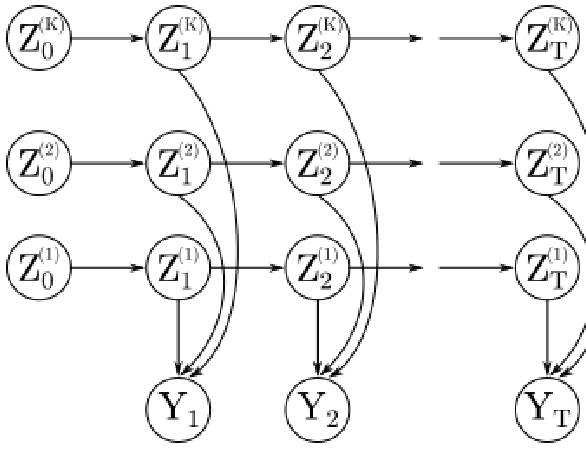

Figure 3.2. The graphical model of the Factorial Hidden Markov Model. Each of the K parallel hidden Markov chains models a single appliance.

3.3 Markov Indian Buffet Process

Griffiths and Ghahramani introduced a prior probability distribution for nonparametric Bayesian factor models called the Indian Buffet Process (IBP) (2006). The IBP defines a probability distribution over infinite-dimensional binary matrices $\mathbf{Z}$, where each element z_{nk} denotes whether datapoint n has feature k or not. A full description of the model and a culinary metaphor for the Markov dynamics of the IBP can be found in the original paper.

The data points in IBP are fully exchangeable, meaning that the features do not follow Markov dynamics. The Markov Indian Buffet Process (MIBP) is an extension of the IBP in which each column of the binary matrix $\mathbf{Z}$ evolves according to a Markov process. In time series settings, **Z** has T rows (time steps) and potentially infinite columns (latent features). In the MIBP each column k of **Z** evolves according to the transition matrix

$$\mathbf{W}^{(k)} = \begin{pmatrix} 1-\mu_k & \mu_k \\ 1-b_k & b_k \end{pmatrix},$$

where $\mathbf{W}^{(k)}_{ij} = p(z_{t+1,k} = j | z_{t,k} = i)$. Each column is initialized with a zero state $z_{0k} = 0$. Then, the state of kth appliance follows $Bernoulli(\mu_k^{1-z_{t-1,k}} b_k^{z_{t-1,k}})$. Finally, a prior distribution is placed on $\mu_k \sim Beta(\alpha/K, 1)$, $b_k \sim Beta(\gamma, \delta)$, where K is the number of features. In the infinite limit the distribution of the equivalence class of **Z** is

$$\lim_{K\to\infty} p([\mathbf{Z}]) = \frac{\alpha^{K_+} e^{-\alpha H_T}}{\Pi_{h=0}^{2^T-1} K_h!} \Pi_{k=1}^{K_+} \frac{(c_k^{01}-1)! c_k^{00}! \Gamma(\gamma+\delta)\Gamma(\delta + c_k^{10})\Gamma(\gamma + c_k^{11})}{(c_k^{00} + c_k^{01})! \Gamma(\gamma)\Gamma(\delta)\Gamma(\gamma+\delta+c_k^{10}+c_k^{11})},$$

where H_t is the t'th harmonic number, c_k^{ij}, $i, j = 0, 1$ is the number of transitions from state i to state j in the column k and K_+ gives the number of columns that contain at least one nonzero entry, which also indicates the effective dimension of the model (van Gael, 2011). The equivalence class of **Z**, [**Z**], is defined as the left-ordered form of the binary matrix **Z** in which the columns are sorted in decreasing order, by binary number representation (Griffiths and Ghahramani, 2006).

The above theoretical description of the MIBP cannot be directly used for inference in infinite FHMM models. However, the stick breaking representation of the IBP is also applicable to the MIBP which provides a distribution law for the order statistics of the appliance state transition parameters μ_k (Teh et al., 2007). Let $\mu_{(k)}$ be the decreasing ordering of variables μ_k, $\mu_{(1)} > \mu_{(2)} > \ldots$. Then, $\mu_{(k)}$ has the following distribution

$$p(\mu_{(1)}) = \alpha \mu_{(1)}^{\alpha-1} \mathbb{I}(0 \leq \mu_{(1)} \leq 1)$$

$$p(\mu_{(k)} | \mu_{(k-1)} = \alpha \mu_{(k-1)}^{-\alpha} \mu_{(k)}^{\alpha-1} \mathbb{I}(0 \leq \mu_{(k)} \leq \mu_{(k-1)}).$$

The variables b_k are all independent draws from their prior $Beta(\gamma, \delta)$ distribution which is independent of K. As such, $b_{(k)}$ also has the same $Beta(\gamma, \delta)$ distribution. This representation makes it possible to use slice sampling and Gibbs sampling for inference, as is shown in section 5.

3.4 Nonparametric Factorial Hidden Markov Model

The Nonparametric Factorial Hidden Markov Model (NFHMM) uses the MIBP as the stochastic model and can be effectively used in unsupervised electricity disaggregation. Because of the nonparametric nature of the MIBP, the number of appliances in the household does not have to be known in advance. Instead, the number of appliances is obtained in inference, together with the binary states of each electrical appliance.

The full Bayesian model used in unsupervised electricity disaggregation introduces a base distribution H from which parameters θ_k are sampled for each Markov chain, representing the power profile of each device in the household. The parameters θ_k are assumed to be normally distributed $\mathcal{N}(\mu_\theta, \sigma_\theta^2)$. Then, the observed signal Y is generated from the model as emission $Y = \mathbf{Z}\theta + \epsilon$, where ϵ is the measurement noise drawn from $\mathcal{N}(/, \sigma_\epsilon)$. The graphical model of NFHMM is shown in figure 3.3 in plate notation.

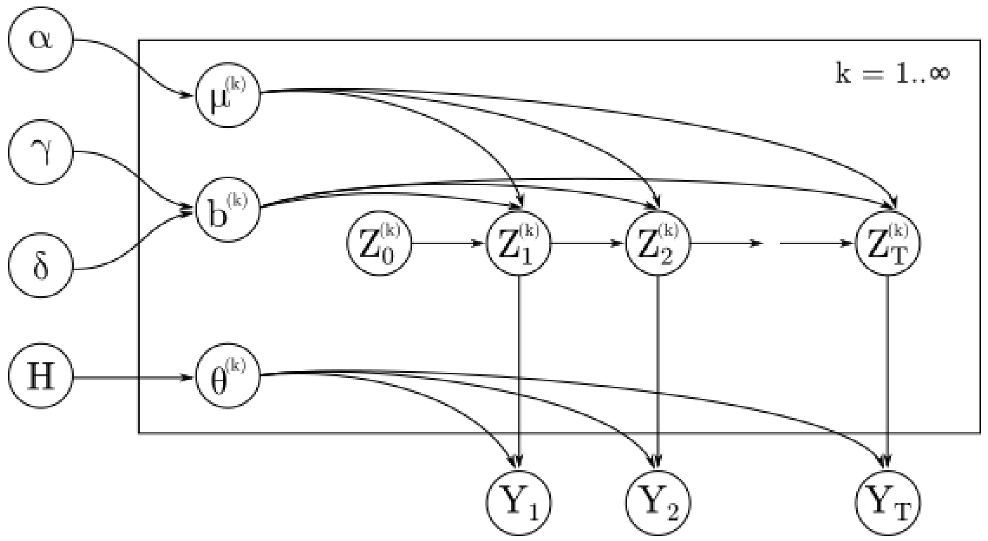

Figure 3.3. The graphical model of the Nonparametric Factorial Hidden Markov Model used in unsupervised electricity disaggregation.

4. Data

The data in this project is comprised of three different datasets described below. The data is from Fortum's pilot elasticity of demand programme. The first two datasets are actual 1 Hz smart meter data from Fortum pilot customer households, whereas the third dataset is a simple synthetic datasets used for testing.

4.1 Fortum datasets

4.1.1 Consumption dataset

The consumption dataset contains the phase specific consumption of 100 Fortum pilot customer households over three weeks in March 2016. The dataset was delivered in 430 CSV files containing a million rows each, totalling 12 GB in storage size. A sample of a consumption file is given in table 4.1.

Table 4.1. Fortum consumption dataset example. The DeviceId defines the building, TypeId the phase and DataValue the current in Amperes.

DeviceId	TypeId	ValueTimeStamp	DataValue
1	1	2016-03-04 21:19:47	4.5
1	3	2016-03-04 21:19:47	9.7
1	2	2016-03-04 21:19:47	1
1	1	2016-03-04 21:19:48	4.5
1	2	2016-03-04 21:19:48	0.7
1	3	2016-03-04 21:19:48	9.7
1	1	2016-03-04 21:19:49	0.7

4.1.2 Boiler dataset

The boiler dataset contains the phase specific consumption of 66 Fortum pilot customer households participating in Fortum's Virtual Power Plant (VPP) demand response program over a one month period in fall 2016. In VPP the participating households' water heater boilers are remote controlled by Fortum according to the real time supply and demand imbalance in the grid. In addition to the electricity consumption data of the participating households, the dataset contains the timestamps of each household's boiler switch commands. The boiler dataset is used in validating the implemented disaggregation model and examining its ability to detect boiler loads from the aggregate data.

The boiler dataset is divided into CSV files with a single file for each household (66 files, 168M lines, 7.5 GB). An example of a consumption data file is given in table 4.2.

Table 4.2. Fortum boiler dataset example. The time is given in UTC, active power in kW, and the currents for the three phases I1, I2 and I3 in Amperes.

DataItemTime	ActivePower	I1	I2	I3
15/10/16 00:00:00	4.333	0.091	7.578	11.172
15/10/16 00:00:01	4.955	2.799	7.577	11.168
15/10/16 00:00:02	5.017	2.982	7.655	11.177
15/10/16 00:00:03	5.421	2.964	7.641	12.969
15/10/16 00:00:04	5.419	2.922	7.622	13.019
15/10/16 00:00:05	5.819	2.922	7.622	14.762
15/10/16 00:00:06	5.744	2.884	7.597	14.494

The boiler command data was given in a single CSV file. The format of the file is shown in table 4.3. In addition to the remote commands, the boilers are controlled by their thermostats, resulting in situations where a boiler is switched on or off before a remote command.

4.2 Synthetic testing datasets

During the development of the NFHMM, it was useful to have testing data with perfect information of device specific consumption i.e. the ground truth data. Such

Table 4.3. Fortum boiler command dataset example. The boilers are commanded to switch on (1) or switch off (-1).

DeviceId	CommandTimeStamp	Command
1	2016-10-15 04:00:01.567	-1
1	2016-10-15 21:00:01.910	1
1	2016-10-16 04:00:00.457	-1
1	2016-10-16 21:00:00.543	1
1	2016-10-17 04:00:01.373	-1
1	2016-10-17 20:59:59.637	1
1	2016-10-18 04:00:01.570	-1

data is not available from Fortum, and open source datasets are unnecessarily large and complex for the early testing phase. Thus we generated our own chunks of data with four different devices for testing the model with and without added noise. This data was then used in model testing and refinement, so that the model output could be compared to the ground truth.

The first synthetic dataset covered a virtual house over 48 hours with 0.1 Hz sampling rate and perfect information (17k lines, < 1 MB storage space). The second synthetic dataset covered two virtual houses over 14 days with 0.1 Hz sampling rate and some generated measurement noise (121k lines, 5 MB). The format of such synthetic datafiles is given in table 4.4.

Table 4.4. Synthetic testing dataset example. The "aggregate" column is the sum of the device consumptions.

timestamp	electric space heater	electric oven	fridge	light	aggregate
01/03/16 02:00:10	1000	0	500	0	1500
01/03/16 02:00:20	1000	0	500	0	1500
01/03/16 02:00:30	1000	0	500	0	1500
01/03/16 02:00:40	1000	0	500	0	1500
01/03/16 02:00:50	1000	0	500	0	1500
01/03/16 02:01:00	1000	0	0	0	1000
01/03/16 02:01:10	1000	0	0	0	1000

5. Implementation

5.1 NFHMM Inference Algorithm

The model parameters of NFHMM are obtained by an approximate inference method. Instead of assigning fixed values to variables, the NFHMM inference algorithm samples variables from their posterior distributions. Gibbs sampling is a commonly used and easily implemented method for sampling variables from their joint distribution. In Gibbs sampling, the variables are updated sequentially after being sampled from the distribution that is obtained by conditioning on the rest of the variables. The first few samples are discarded as the warm up period, after the method samples approximately from the joint distribution of the variables. The order statistics of $\mu_{(k)}$ in the stick breaking representation, described in the theory section, enables the use of slice sampling (Teh et al., 2007). Hence, the inference algorithm of NFHMM is based on the combination of slice sampling and Gibbs sampling. Slice sampling allows the adaptive truncation of the size of the model.

The iterative NFHMM inference algorithm takes the observations as input and follows the steps described in Teh et al. (2007) and Jia et al. (2015):

```
Input
    Aggregate electricity consumption data $Y$.

Initialization
    Initialize $\mathbf{Z}, \mu, b, \theta$ and select iteration number IterNum.

Iteration loop
    while IterNum > 0 do

      1. Sample slice variable $s$ from $p(s|rest) = \frac{1}{\mu^*}\mathbf{1}\{0 \leq s \leq \mu^*\}$,
         where $\mu^* = \min\{1, \min_{k:\exists t, z_{t,k}=1} \mu_{(k)}\}$.
```

2. Expand representation of $\mathbf{Z}, \mu, b, \theta$.

   Let K^* be the maximal index with $\mu_{(k)} > s$ and $K^\dagger$ be an index such that all active appliances have index $k < K^\dagger$. If $K^* \geq K^\dagger$ zero columns are expanded to $\mathbf{Z}$ until $K^* < K^\dagger$. The stick lengths $\mu_{(k)}$ for the new columns are drawn from $p(\mu_{(k)}|\mu_{(k-1)}, z_{:,>k} = 0) \propto \exp(\alpha \sum_{i=1}^{N} \frac{1}{i}(1-\mu_{(k)})^i)\mu_{(k)}^{\alpha-1}(1-\mu_{(k)})^N \mathbf{1}\{0 \leq \mu_{(k)} \leq \mu_{(k-1)}\}$ with Adaptive Rejection Sampling (ARS), while the remaining parameters are drawn from their respective prior distributions.

3. Sample $\mathbf{Z}$ from $p(z_{:,k}|rest) \propto p(Y|\mathbf{Z},\theta)p(s|\mathbf{Z},\mu)p(z_{:,k}|\theta, b)$ using a blocked Gibbs sampler and Forward Filtering Backward Sampling (FFBS). The slice variable s ensures that the columns of $\mathbf{Z}$ for which $\mu_{(k)} < s$ are zero columns. After sampling, delete any zero columns $k < K^*$ of $\mathbf{Z}$ and their corresponding parameters.

4. Sample θ_k from $p(\theta_k|rest) \sim \mathcal{N}(\sigma^2_{\theta;p}(\frac{\mu_\theta}{\sigma^2_\theta} + \frac{1}{\sigma^2_\epsilon}\sum_t z_{t,k}(Y_t - \sum_{i\neq k} z_{t,i}\theta_i)), \sigma^2_{\theta,p})$, where $\sigma^2_{\theta;p} = (\frac{1}{\sigma^2_\theta} + \sum_t z_{t,k}\frac{1}{\sigma^2_\epsilon})^{-1}$.

5. Sample $\mu_{(k)}$ from $p(\mu_{(k)}|rest) \propto (1-\mu_{(k)})^{c^{00}_{(k)}}\mu_{(k)}^{c^{01}_{(k)}-1}\mathbf{1}\{\mu_{(k+1)} \leq \mu_{(k)} \leq \mu_{(k-1)}\}$ using ARS.

6. Sample $b_{(k)}$ from $p(b_{(k)}|rest) \propto (1-b_{(k)})^{c^{10}_{(k)}+\delta-1} b_{(k)}^{c^{11}_{(k)}+\gamma-1}$.

7. Sample hyperparameters $\alpha, \delta, \gamma, \mu_\theta, \sigma^2_\theta, \sigma^2_\epsilon$ from their posterior distributions.

8. `IterNum` $\leftarrow$ `IterNum - 1`.

Output

Binary matrix $\mathbf{Z}$ and device power levels θ.

Step 7 of the while loop requires imposing appropriate conjugate prior distributions to the hyperparameters. In this project work, however, a heuristic is used for sampling σ_ϵ based on the median of the first order differences of $Y - \mathbf{Z}\theta$. Additionally, the output is by default only a sample of the last iteration, drawn from the approximate joint distribution of the parameters. In order to obtain maximum likelihood estimates, the likelihoods of $\mathbf{Z}$ and θ need to be evaluated and stored for each iteration.

5.2 Non-Intrusive Load Monitoring Toolkit

In order to explore and use our datasets with NILMTK they had to be reorganized according to the NILM metadata specification. We developed a script to reorganize the data from Fortum's consumption dataset such that data from each meter (three for current and one for total power) was its own CSV file with a very simple format. Additionally metadata was developed for Fortum's consumption dataset and the two synthetic datasets according to NILM Metadata specification version 0.2. The metadata allows NILMTK to process and organize the data for the disaggregation problem. Then dataset converters were implemented in NILMTK for the three datasets to convert the CSV data into the HDF5 format used by NILMTK to store data internally. Finally, a wrapper for the NFHMM algorithm implemented in R was developed for NILMTK to be able to utilize it through the toolkit for instance to explore its performance against datasets and disaggregation algorithms already adapted or implemented for the toolkit.

The current implementation of the NFHMM wrapper makes testing and comparing the algorithm with NILMTK datasets and benchmark algorithms possible but not ideal. The wrapper iterates through the data-to-be-disaggregated in large chunks and forwards them one by one to the actual NFHMM algorithm for disaggregation. Three parameters are forwarded along with the data chunk: initial guess of the number of appliances, the sigma epsilon heuristic parameter and the number of sampling iterations. Because the non-deterministic disaggregation process may get stuck in infinite loops in cases of bad input heuristic parameters, the wrapper will terminate the process if the execution takes too long. It also attempts to finish the disaggregation process five times before giving up with the chunk. This design makes it possible to apply the algorithm for even big datasets rather conveniently. The data chunk and disaggregated appliance time series are communicated through a simple file-based interface using the pandas library at the NILMTK end. The wrapper as well as the algorithm were adjusted to display helpful messages to facilitate the monitoring of progress. This is useful, because as each chunk is disaggregated independently with no learning going on across chunks, it is important that each chunk is big enough to represent each appliance properly, which might make each chunk take several minutes of processing time.

The comparison of supervised against unsupervised algorithms is nontrivial. For instance, as NFHMM estimates the number of appliances and their consumption patterns entirely, no found appliance consumption pattern can directly be compared with those from supervised algorithms. Most comparison functions in NILMTK require that the number of time series is identical to the number of meters in the metadata which led to the simplification in the current implementation of the NFHMM wrapper in NILMTK to completely disregard any found excess appliances. Also, in the current implementation, there is no attempt to match the found patterns with the ground truth patterns such as to facilitate automatic numeric analysis of disaggregation accuracy. Thus computing f-scores, for example, with NILMTK to compare performance can be misleading and unfruitful.

More information and examples on how to utilize the toolkit with the described extensions is available online at https://github.com/smarisa/nilmtk. The snippet below gives a rough Python script outline on how data from Fortum can be disaggregated using our NFHMM algorithm with NILMTK:

```
# Convert the CSV data from a directory into HDF5 format
convert_fortum('data/fortum_test', 'data/fortum_test/fortum_test.h5')
# Open the dataset and disaggregate it using NFHMM
dataset = DataSet('data/fortum_test/fortum_test.h5')
nfhmm = NFHMMDisaggregator()
output = HDFDataStore('output.h5', 'w')
nfhmm.disaggregate(dataset.buildings[1].elec.mains(), output,
    max_appliances=10)
output.close()
# Plot the disaggregation results into a PNG file
results = DataSet('output.h5')
ax = results.buildings[1].elec.plot()
ax.set_title("NFHMM disaggregation results")
plt.savefig('results.png')
plt.clf()
```

6. Results

6.1 Validation with generated dataset

We validate the accuracy of the algorithm by comparing the output of the algorithm with the electrical signals in the synthetic dataset. The validation is easily carried out with the synthetic dataset, because all the individual electrical appliances' signals and power levels are known, as well as the noise in their aggregate signal. We use two error metrics to calculate the error in the real aggregate signal and the obtained aggregate signal. The mean absolute error (MAE) is defined as

$$MAE = \frac{1}{N} \Sigma_{t=1}^{T} |y_t - \epsilon_t - Z_t \theta|.$$

The mean absolute percentage error is defined as

$$MAPE = \frac{1}{N} \Sigma_{t=1}^{T} |\frac{y_t - \epsilon_t - Z_t \theta}{y_t}|.$$

Figure 6.1 shows the synthetic input data used to validate the NFHMM algorithm. The input data consists of 23 minutes of electrical measurements with low noise, $\epsilon_t \sim \mathcal{N}(0, 10)$. The shown aggregate signal is the sum of the individual appliances' signals. Figure 6.2 shows the separate electrical appliances present in the input data.

The output of the NFHMM algorithm is shown in figure 6.3 and 6.4. The mean absolute error of the NFHMM output aggregate signal is MAE = 76.0 and the mean absolute percentage error is MAPE = 0.13. The output aggregate signal matches the input quite well, and the individual electrical appliances' consumption signals seem reasonable. The main difference in the input and output individual appliance signals is the "mirroring" of the signals corresponding to the oven and the heater signals in the input data. In the input data the oven signal is a two-event on-off signal, and the heater signal is periodic throughout the whole time series. In

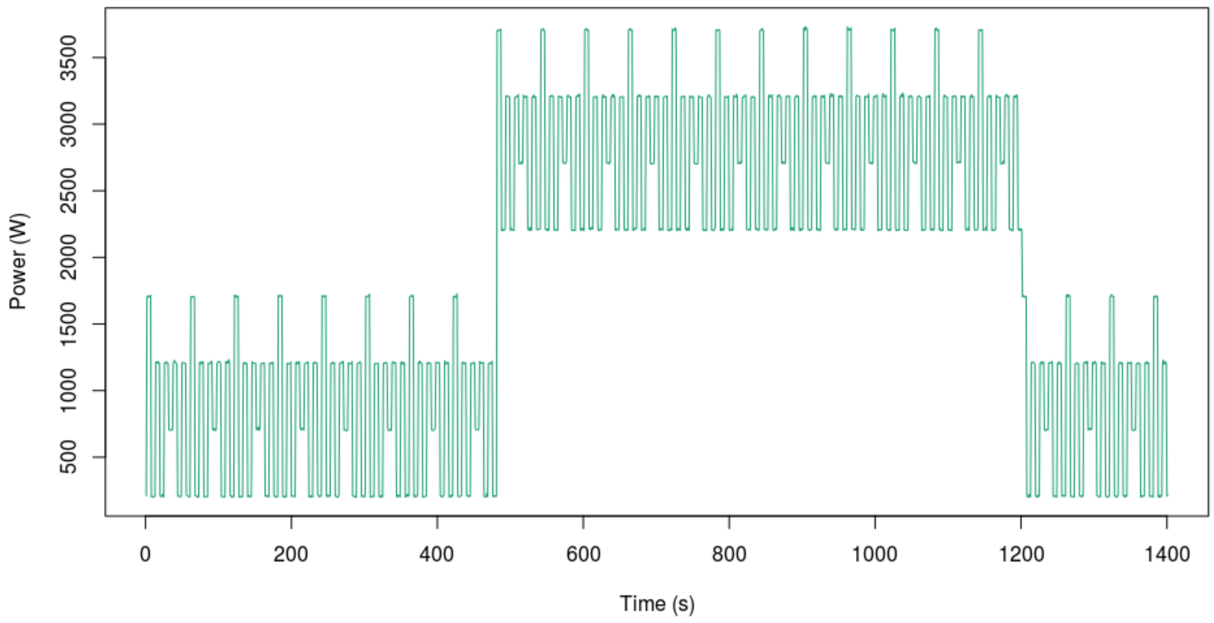

Figure 6.1. The synthetic aggregate signal used as input for the NFHMM algorithm.

the output signals this behaviour is reversed, because the signal corresponding to the input oven signal is periodic in the middle of the time-series, whereas the signal corresponding to the input heater signal stops being periodic in the same time frame. Additionally, the power levels of the appliances corresponding to light, fridge and heater are slightly overestimated, whereas the appliance corresponding to oven is underestimated. The real and computed values of the power levels are shown in table 6.1.

Table 6.1. The real and computed appliance power levels.

	Real	Computed
Light	200	294
Fridge	500	881
Heater	1000	1287
Oven	2000	1578

Because the NFHMM algorithm is not deterministic, it is possible for the algorithm to converge to a local optimum where the extracted number of appliances is not the same as in the input. An example of such a case is shown in figure 6.5 and

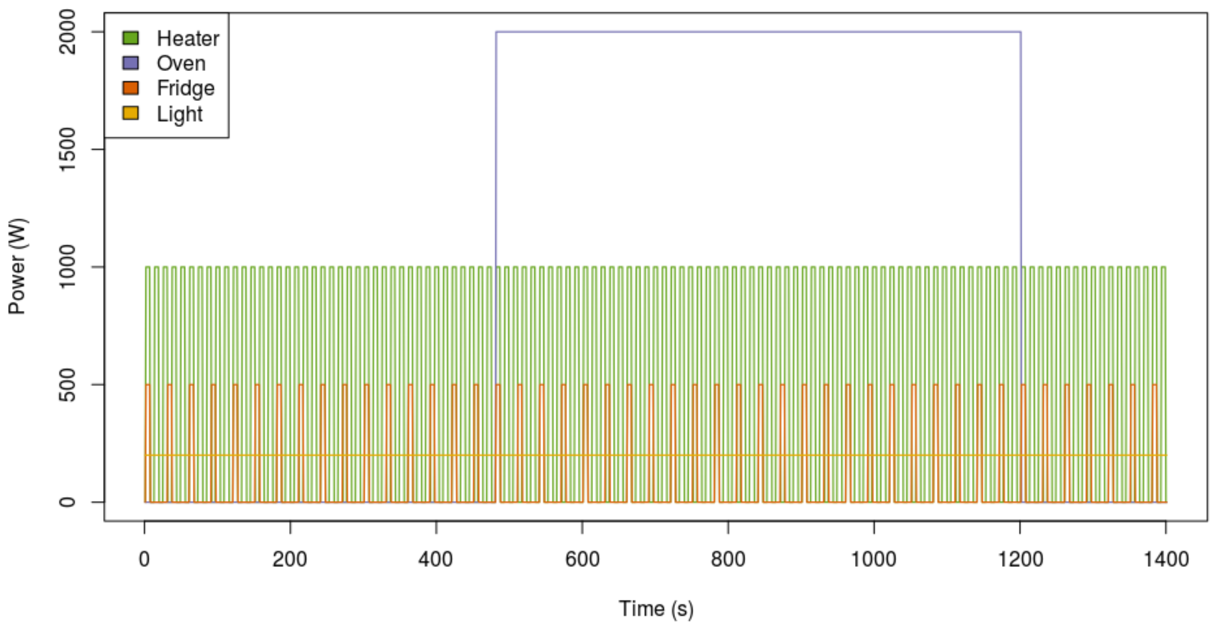

Figure 6.2. The separate electrical appliances present in the input of the NFHMM algorithm.

6.6.

We also tested the disaggregation accuracy of the NFHMM algorithm using the same generated data, but with noise $\epsilon_t \sim \mathcal{N}(0, 100)$. The noisy input data is shown in figure 6.7.

The NFHMM output for the noisier input data is shown in figures 6.8 and 6.9. As seen in the figures, the algorithm seems to be quite robust and is able to estimate the noise and produce sensible results, even with high noise. The output aggregate signal errors are somewhat higher, MAE = 96.6 and MAPE = 0.16. Additionally, the added noise makes the NFHMM algorithm more prone to converge to a local optimum, and required several runs to produce a sensible result.

6.2 Performance comparison using NILMTK

NILMTK's CO and FHMM implementations can be used to benchmark the disaggregation performance of the developed NFHMM algorithm. Using a script we developed (`comparison.py`), NILMTK can be used to train the supervised algorithms and apply them to disaggregate the data. In this comparison, we ran the script

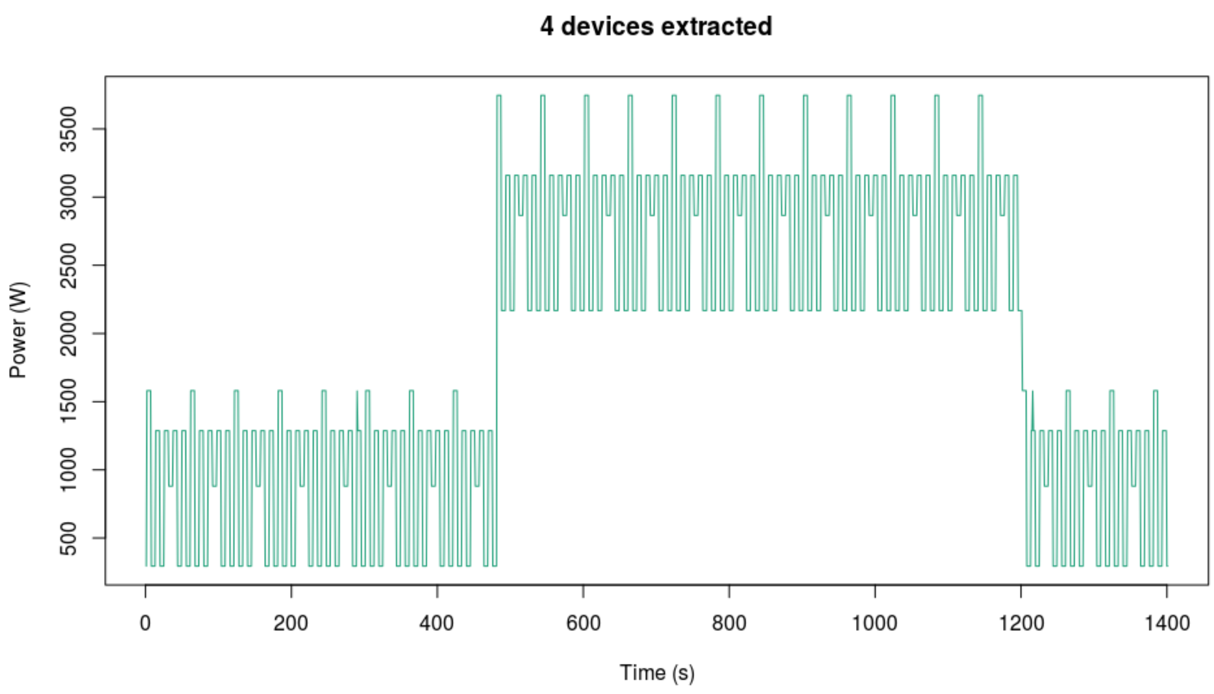

Figure 6.3. The NFHMM output aggregate signal. The algorithm is able to extract the correct number of electrical appliances in the household.

with two synthetic datasets in turn. In the first dataset only one building exists so it was wholly used for both training and disaggregation and in the second dataset the first building was used for training and the second for disaggregation. Examples of the two datasets are shown in figures 6.10 and 6.11, whereas the wiring hierarchy of the two synthetic datasets is shown in figure 6.12. NILMTK's plotting and metrics functionality were used to generate the results.

In the case of the first dataset, where the same data was used for both training and disaggregation, the supervised CO and FHMM algorithms performed excellently. With the second dataset, where there was some difference between the training and disaggregation datasets, some error began to appear in their performance. However, the NFHMM algorithm did not reach the level of either supervised algorithm using such perfect data as can be read from table 6.2.

It should be noted that the comparison of supervised against unsupervised algorithms with perfect or near perfect data is unfair. The limitations of the current implementation of the NILMTK integration must also be noted. As explained in chapter 5, NFHMM is sometimes unable to correctly determine the number of appliances and the current implementation of the NFHMM wrapper in NILMTK sim-

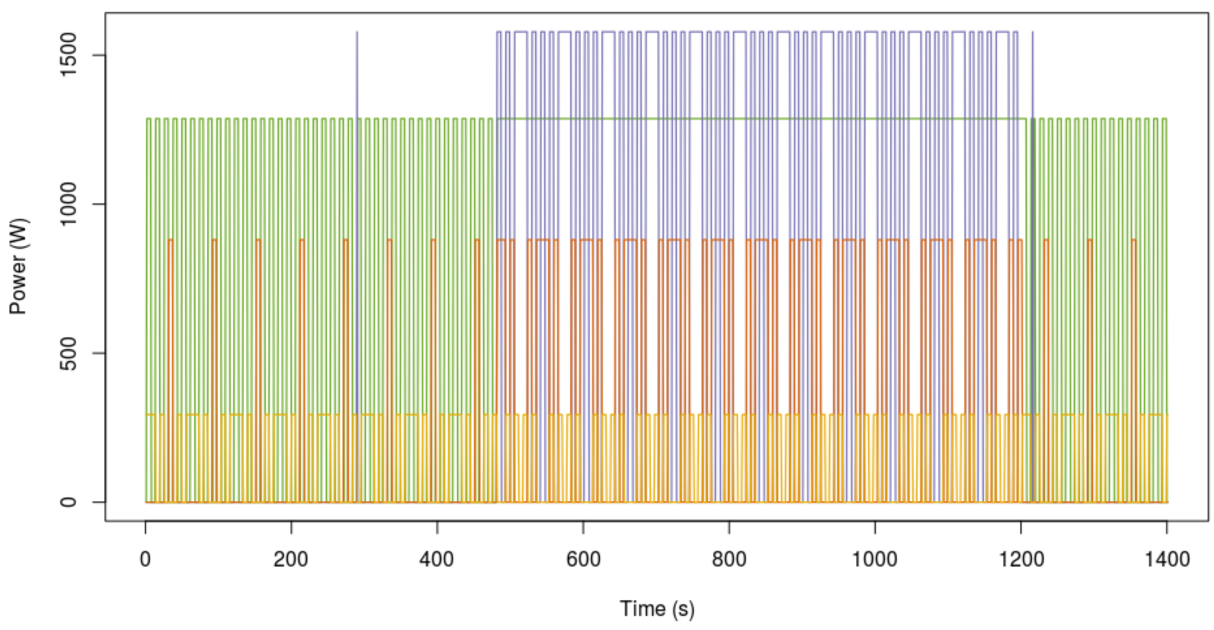

Figure 6.4. The NFHMM output of the individual electrical appliances' consumption.

ply disregards any found excess appliances and compares just the first four of the found appliances against the ground truth. This makes simple f-score comparison unflattering and thus complicates comparison.

However, during testing we found that when the frequency and number of data points is sufficiently high, the algorithm tends to find the correct number of devices with suitable heuristic parameter values. To explore performance with different parameter combinations, three parameters were varied: The sigma epsilon heuristic parameter (HP), the number of sampling iterations (SI) and the sampling period or data frequency (SP). The NFHMM columns of the table 6.2 describe the best of six runs with different parameter combinations. The parameter combination that produced the best results for dataset 1 was 20, 120, 10 and the best for dataset 2 was 10, 60, 10, respectively. It should be noted that the process is not deterministic and much computing resources would be required to produce a good distribution of results to yield confidence in the optimality of any parameter combination for a dataset.

Figure 6.13 provides an example of a NFHMM disaggregation result in a case where the algorithm managed to correctly divide the consumption among four ap-

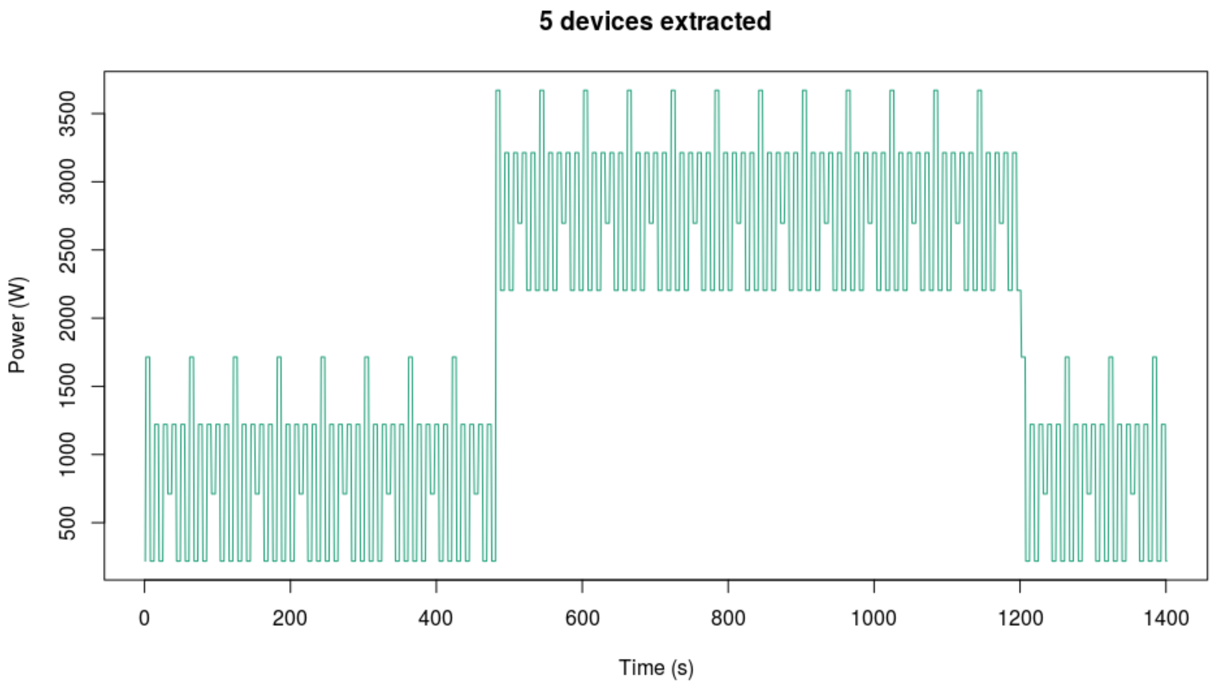

Figure 6.5. The NFHMM output aggregate signal. The algorithm extracts an extra electrical appliance compared to the input.

pliances. While the number of found appliances was correct, the results are still poor when compared against for example FHHMs disaggregation plot depicted in figure 6.14.

However, when the algorithm was reapplied with twice as many sampling iterations it was not only able to determine the number of appliances but also yield much better results otherwise as shown in figures 6.15 and 6.16. However, increasing the number of sampling iterations incurs costs in time since the time complexity of the algorithm is linear to the number of iterations. Running 60 iterations over the 121k data points with NFHMM took 13 minutes while running both the training and disaggregation phases with CO and FHMM took just a few minutes each.

Again doubling the number of iterations to 120 did not improve the results. The results in figure 6.17 show that while the increase in time consumption doubled in linear fashion to 27 minutes the quality of the results did not. In fact, while the number of found appliances was yet again correct, the predicted consumption levels and patterns were not.

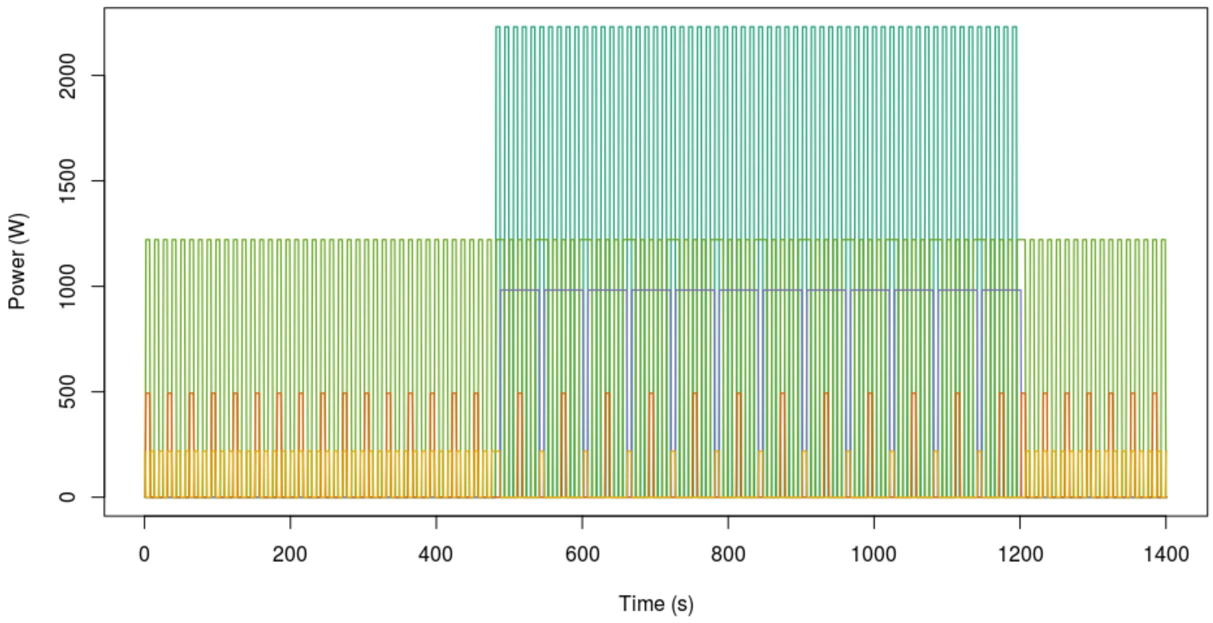

Figure 6.6. The NFHMM output of the individual electrical appliances' consumption, where the algorithm has extracted an extra appliance.

6.3 Disaggregating Fortum datasets

The implemented NFHMM algorithm was used to disaggregate the data given by Fortum. Figure 6.18 shows a 20 minute segment of a Fortum pilot customer household electricity consumption.

The NFHMM algorithm was run for 200 iterations resulting in 4 extracted appliances. The output aggregate signal is shown in figure 6.19 and the individual appliances' consumption is shown in figure 6.20.

On some runs the NFHMM algorithm converged to a solution with 3 appliances. An example of such an output aggregate signal and the individual appliances' signals is shown in figures 6.21 and 6.22.

We also used the NFHMM algorithm to disaggregate a segment from a Fortum pilot customer household containing a boiler switch event. Figure 6.23 shows the data that was used, containing a roughly 3 kW boiler switch-on event at the 700 second mark.

The NFHMM algorithm was run again for 200 iterations resulting now in 5 extracted appliances. The NFHMM output aggregate signal is shown in figure 6.24,

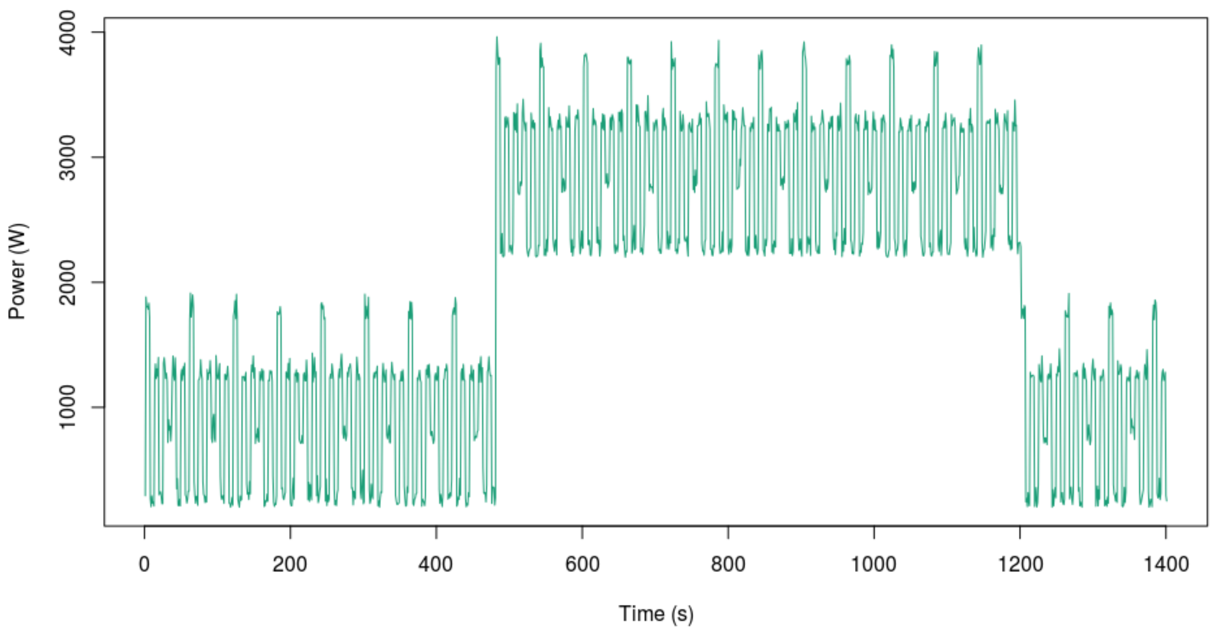

Figure 6.7. The generated noisy aggregate signal used as input of the NFHMM algorithm.

and the individual appliance consumptions are shown in figure 6.25. The algorithm extracted a 2.89 kW appliance, which can be seen in figure 6.25. The boiler switch-on event is detected and maintained quite well, however, the appliance corresponding to the boiler is also detected as being active before the switch-on event, for very short durations.

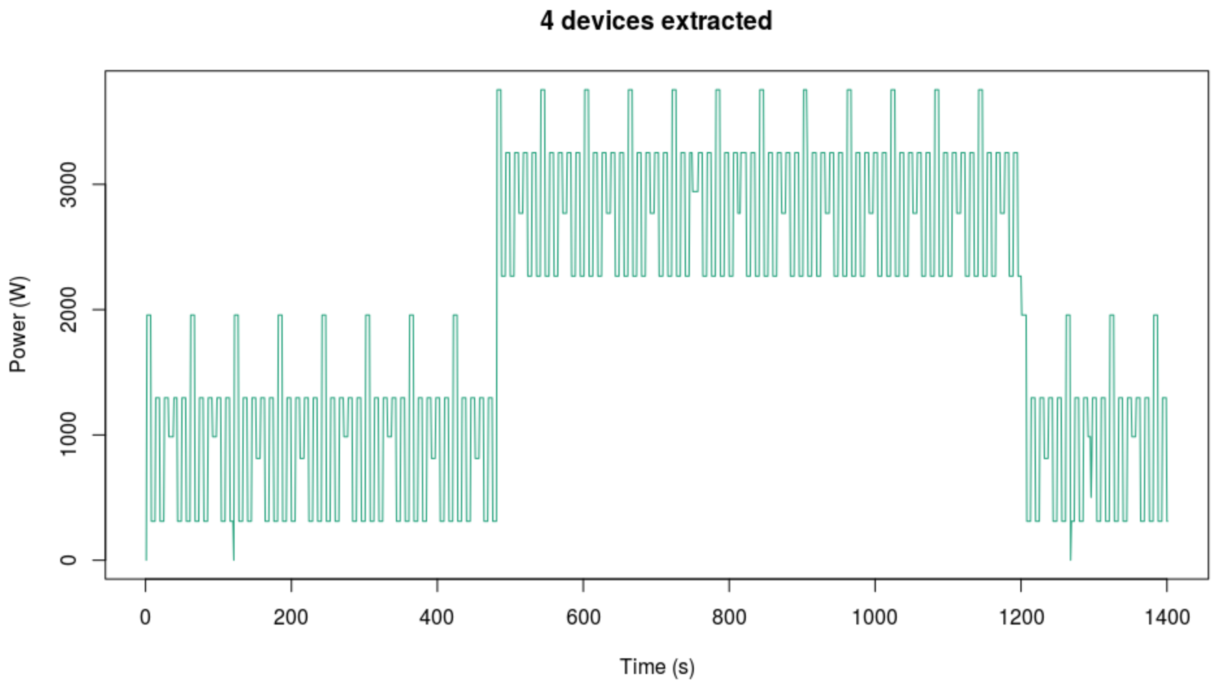

Figure 6.8. The NFHMM output aggregate signal for the noisier input. The algorithm is still able to extract the correct number of electrical appliances.

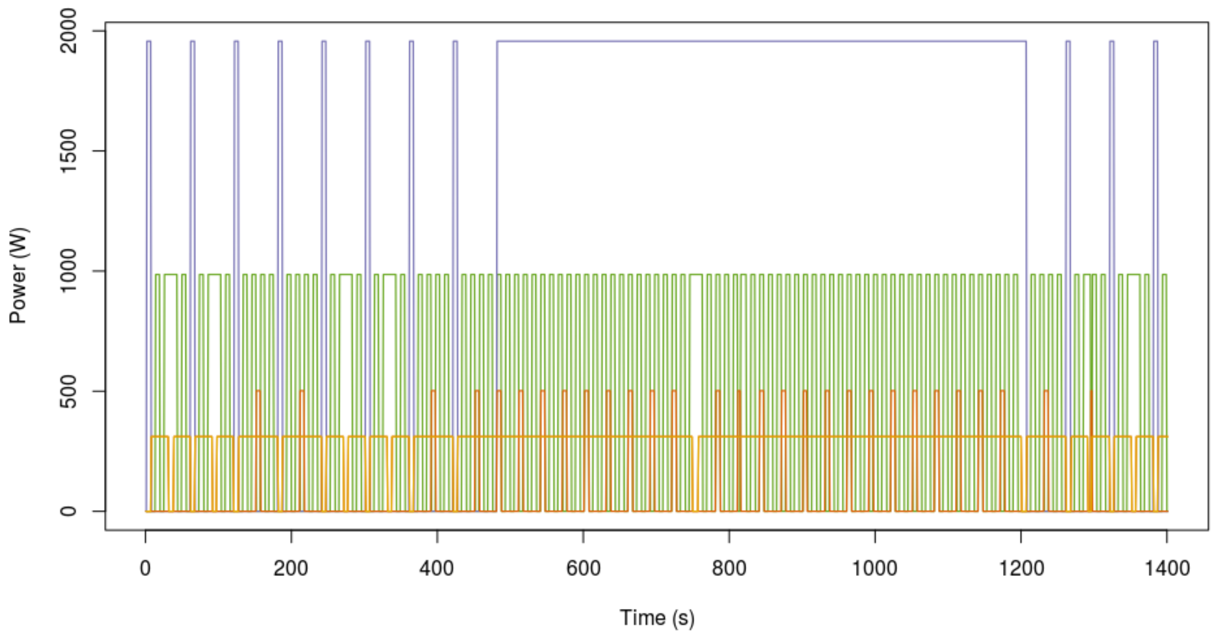

Figure 6.9. The NFHMM output of the individual electrical appliances' consumption for the noisier input.

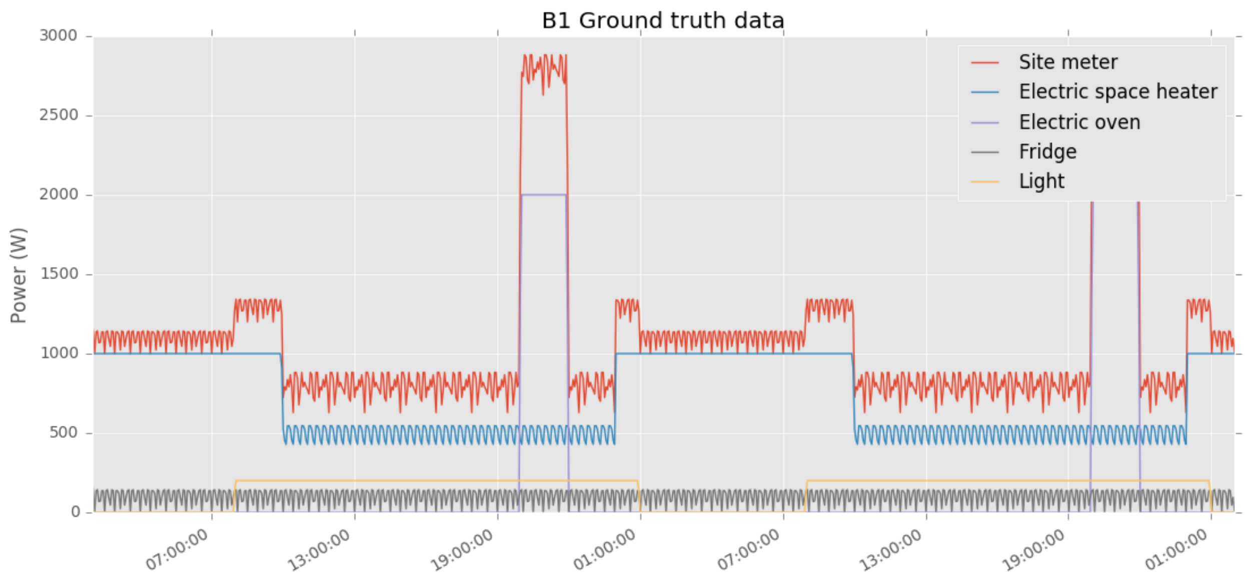

Figure 6.10. A plot of the ground truth data of the only building of the first synthetic dataset.

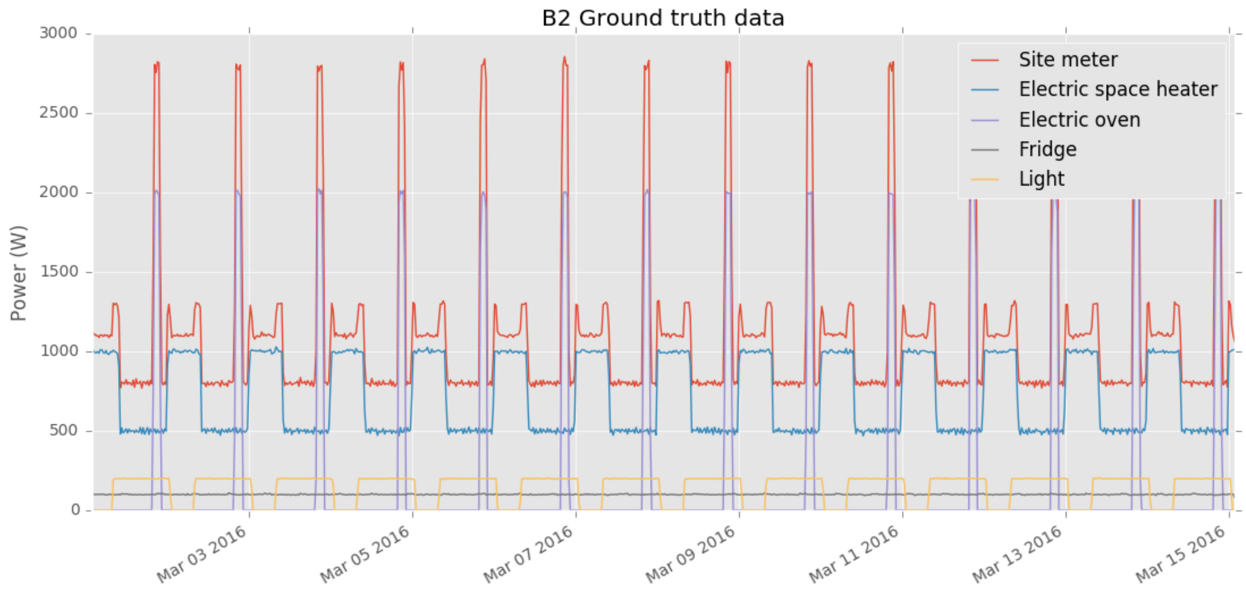

Figure 6.11. A plot of the ground truth data of the second building of the second synthetic dataset. Note that the data is essentially the first dataset repeated and with added noise. Only noise makes the first building different from the second.

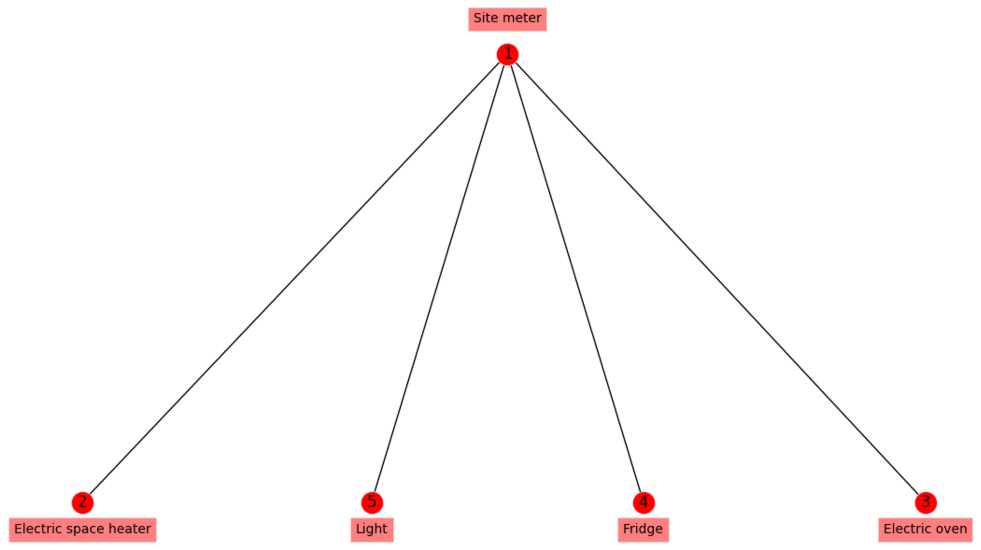

Figure 6.12. A graph depicting the wiring hierarchy of the meters in all buildings of the two synthetic datasets.

Table 6.2. F-scores of the algorithms with both datasets.

Appliance	Dataset 1 (perfect)			Dataset 2 (noisy)		
Method	CO	FHMM	NFHMM	CO	FHMM	NFHMM
Light	1.00	1.00	0.6	0.96	0.97	0.9
Fridge	1.00	1.00	0.8	0.95	0.98	0.5
Electric oven	1.00	1.00	0.7	1.00	1.00	0.5
Electric space heater	1.00	1.00	0.7	1.00	1.00	0.9

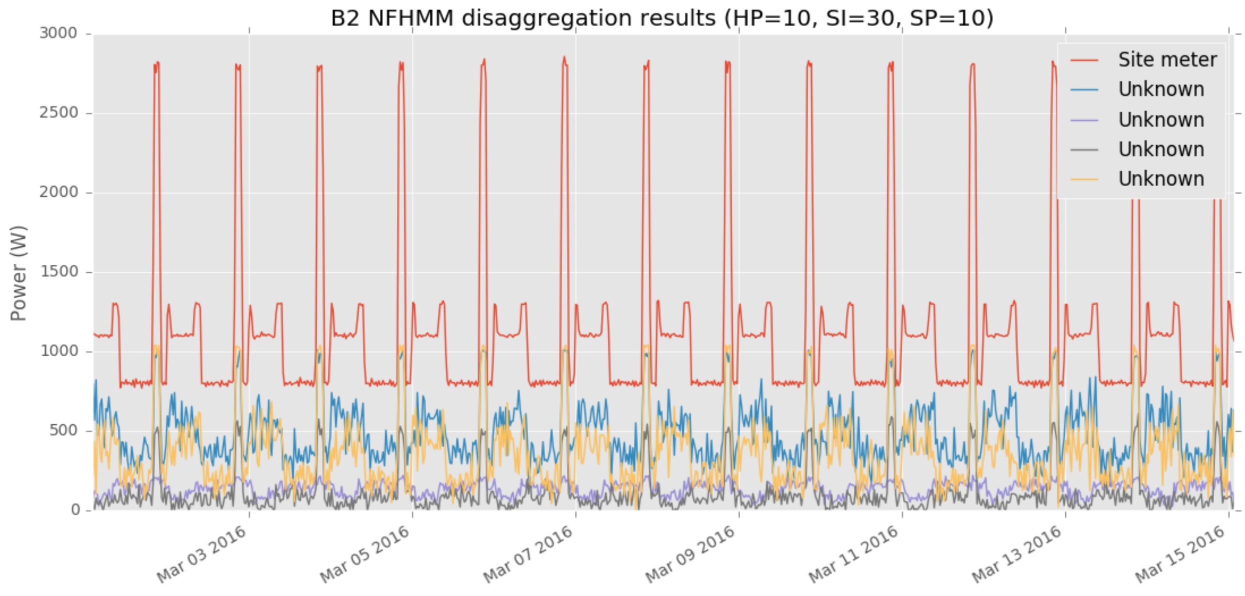

Figure 6.13. Disaggregation result from a run which successfully determined the number of appliances but failed to otherwise produce clean results.

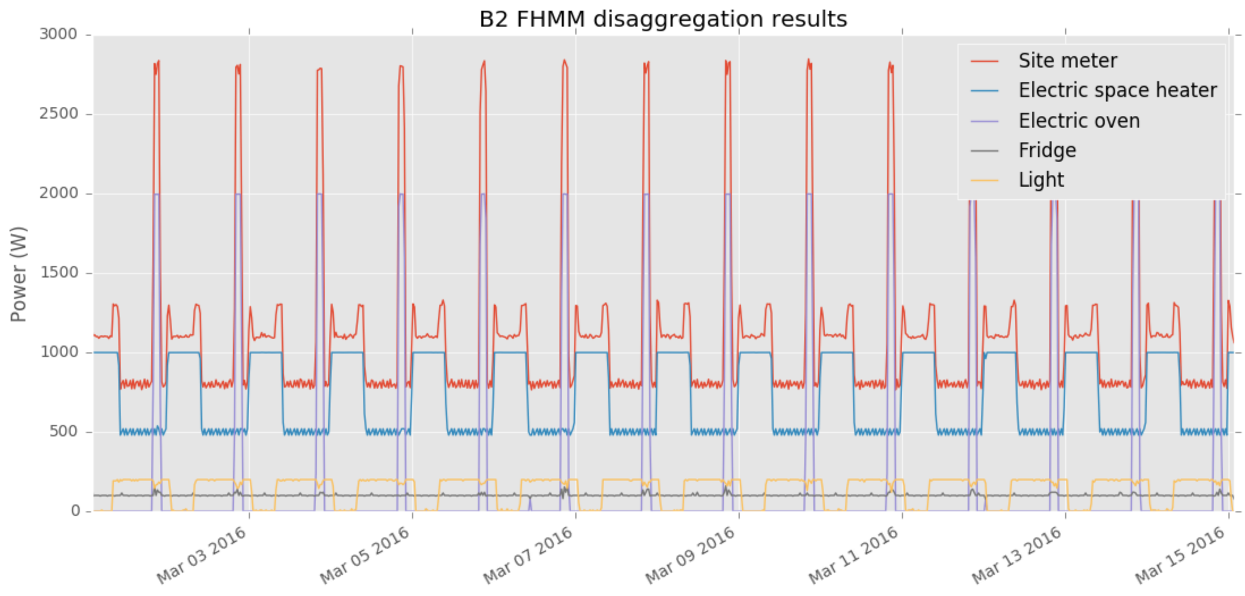

Figure 6.14. Disaggregation results using the implementation of FHMM available in NILMTK. By comparing this plot with the ground truth depicted in figure 6.10 one can visually affirm the results depicted in table 6.2 and conclude that FHMM was able to perform excellently with this dataset.

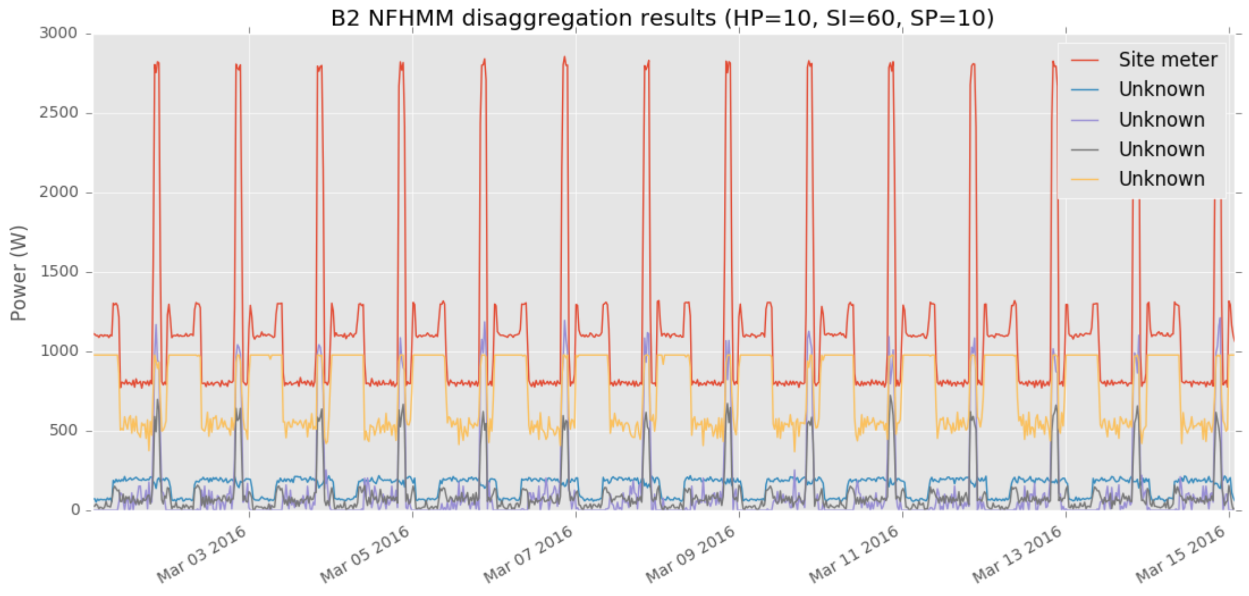

Figure 6.15. Disaggregation result from a run with twice as many sampling iterations as in the run depicted in figure 6.13.

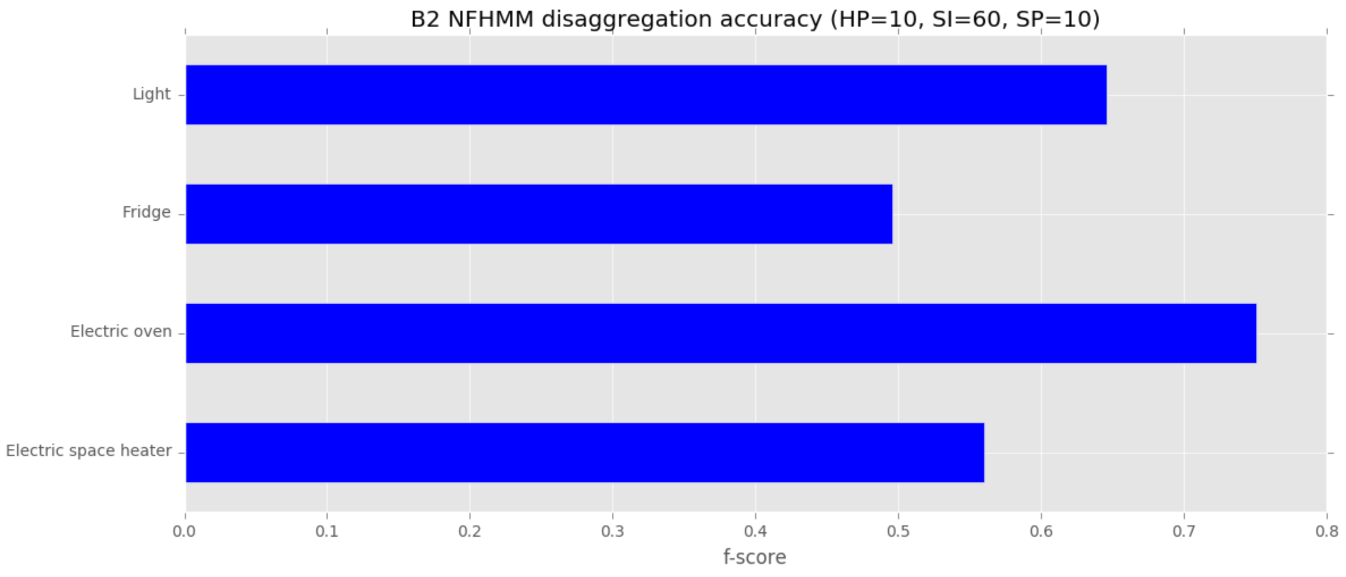

Figure 6.16. Disaggregation accuracy plot corresponding to figure 6.15. However, note that the validity of the accuracy plot is not good because the mapping of disaggregated appliance consumption time series to these four appliances was done simply in sequential order. This is why the values presented in table 6.2 were manually adjusted.

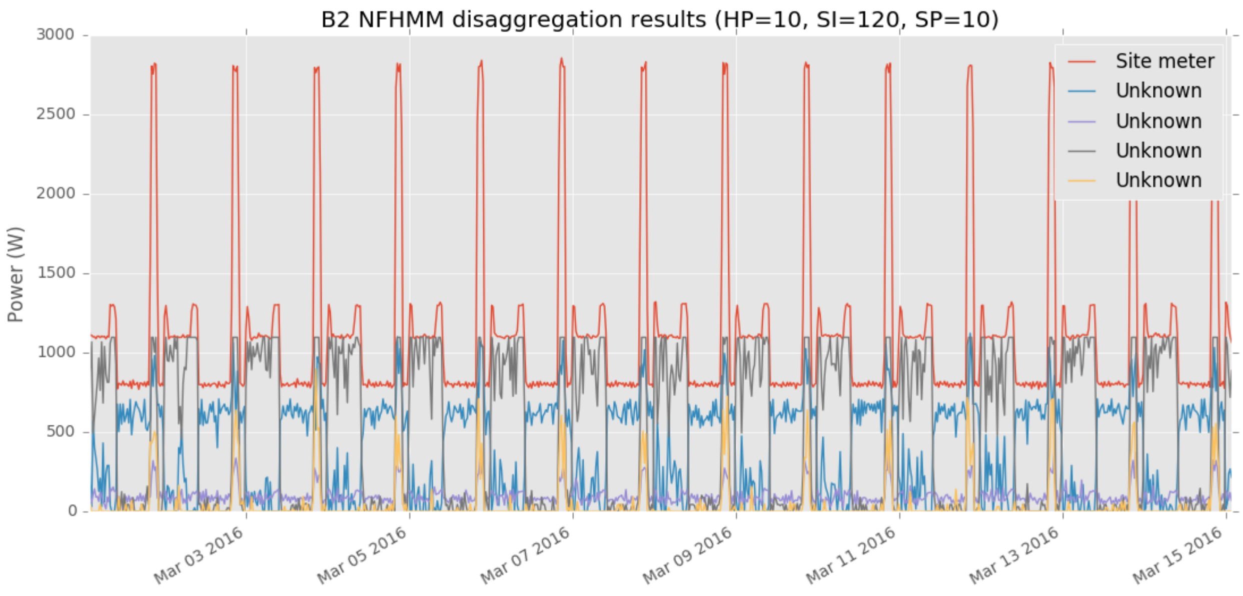

Figure 6.17. NFHMM disaggregation results with 120 sampling iterations.

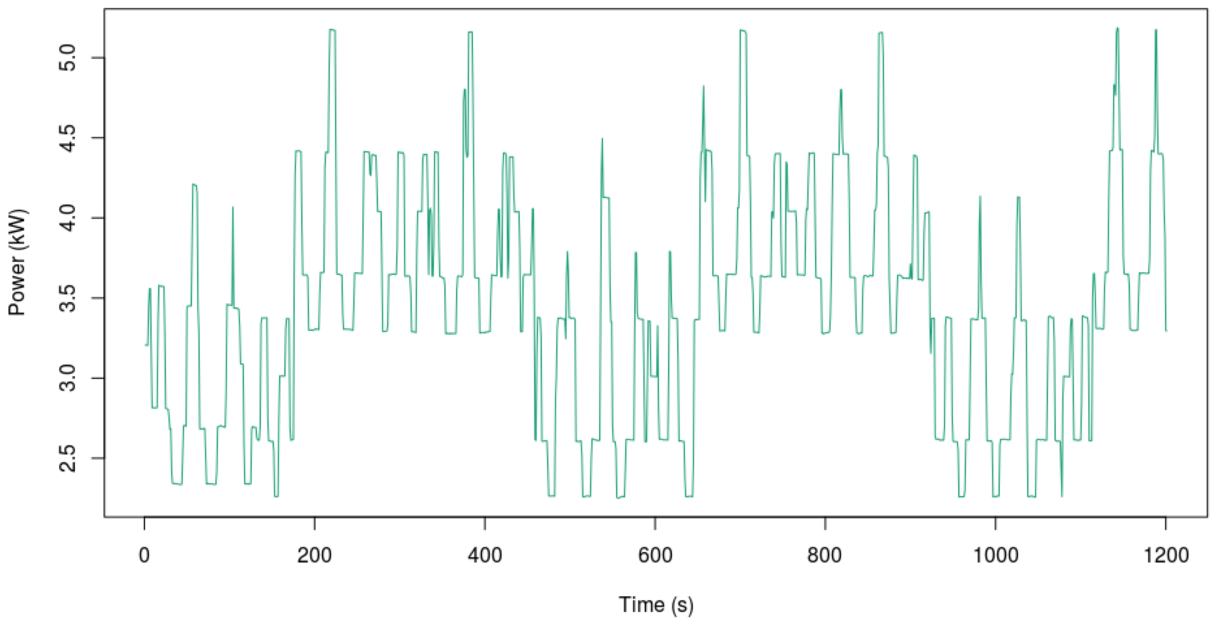

Figure 6.18. The Fortum pilot customer household electricity consumption that was disaggregated with the fully unsupervised NFHMM algorithm.

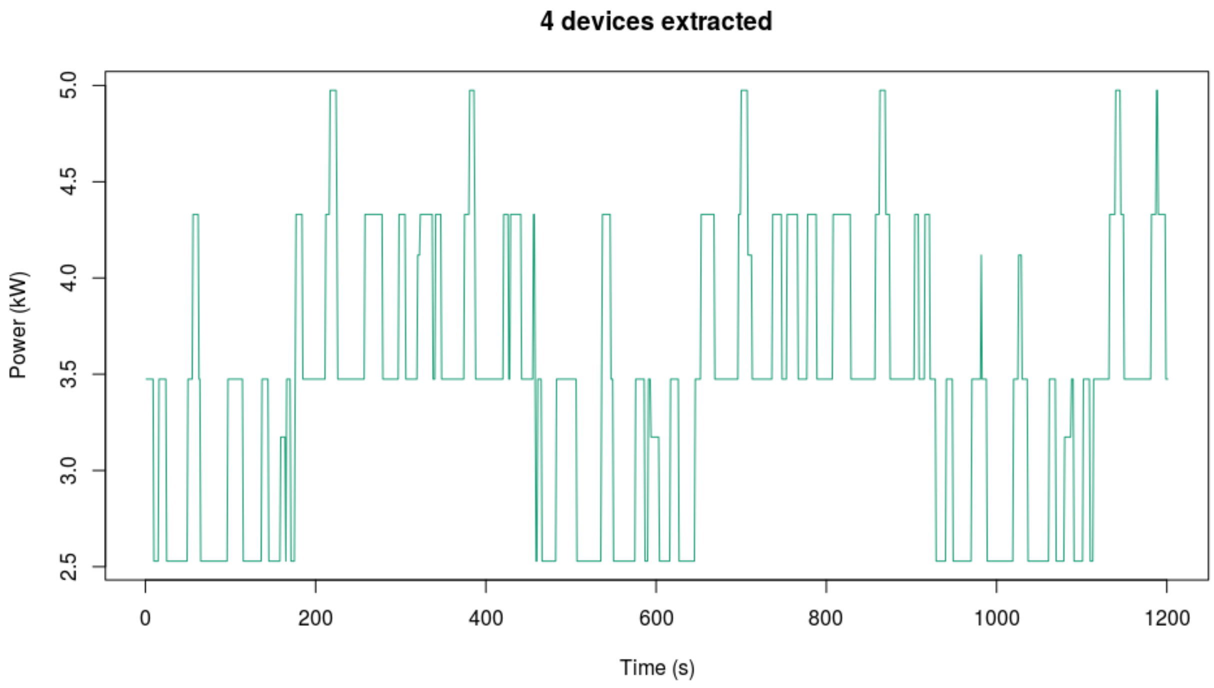

Figure 6.19. The NFHMM output aggregate electricity consumption signal for the Fortum household data. The algorithm extracted 4 individual appliances.

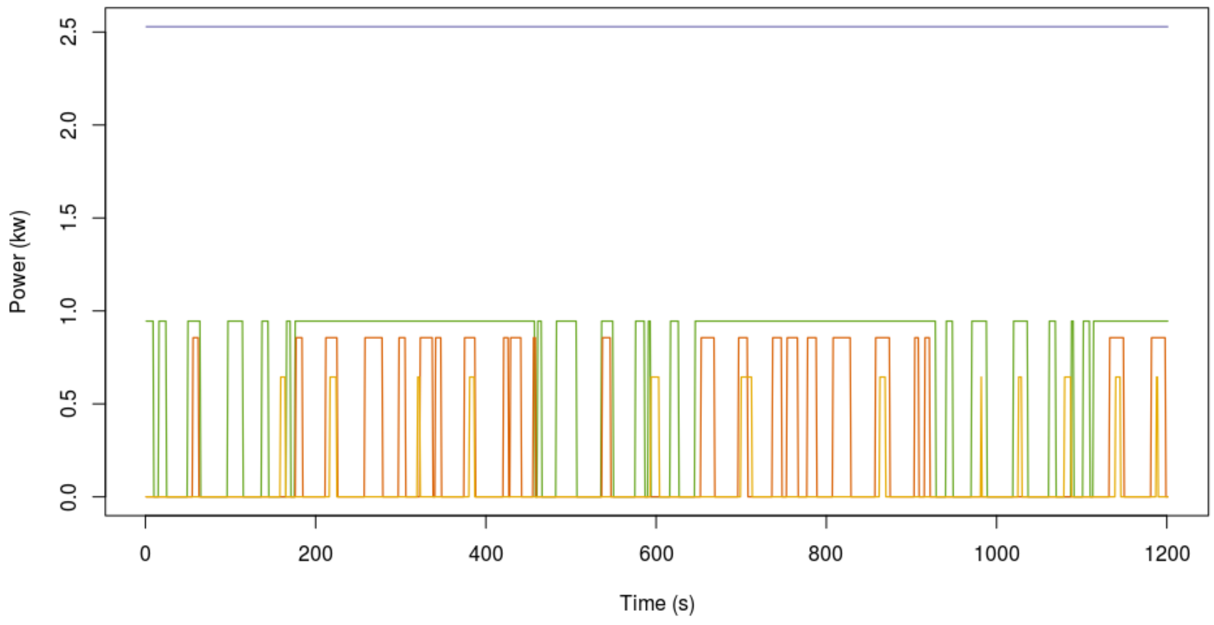

Figure 6.20. The NFHMM output of the 4 individual appliances' in the Fortum household.

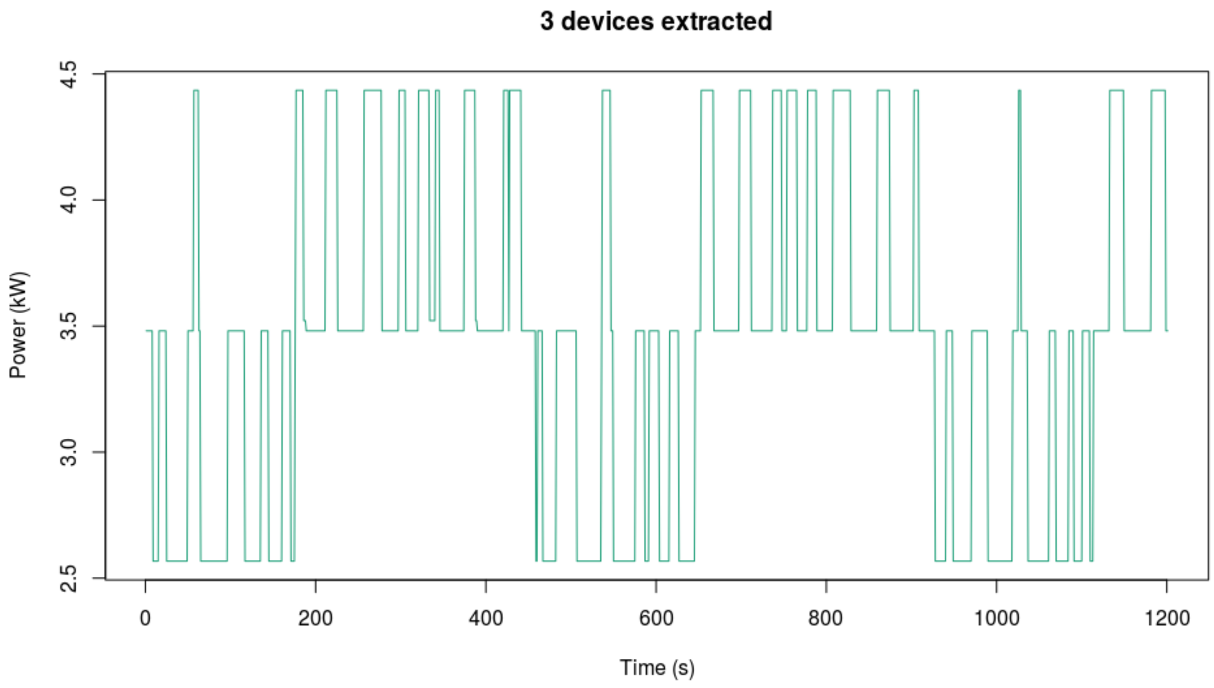

Figure 6.21. The NFHMM output aggregate electricity consumption signal for the Fortum household data. The algorithm extracted 3 individual appliances.

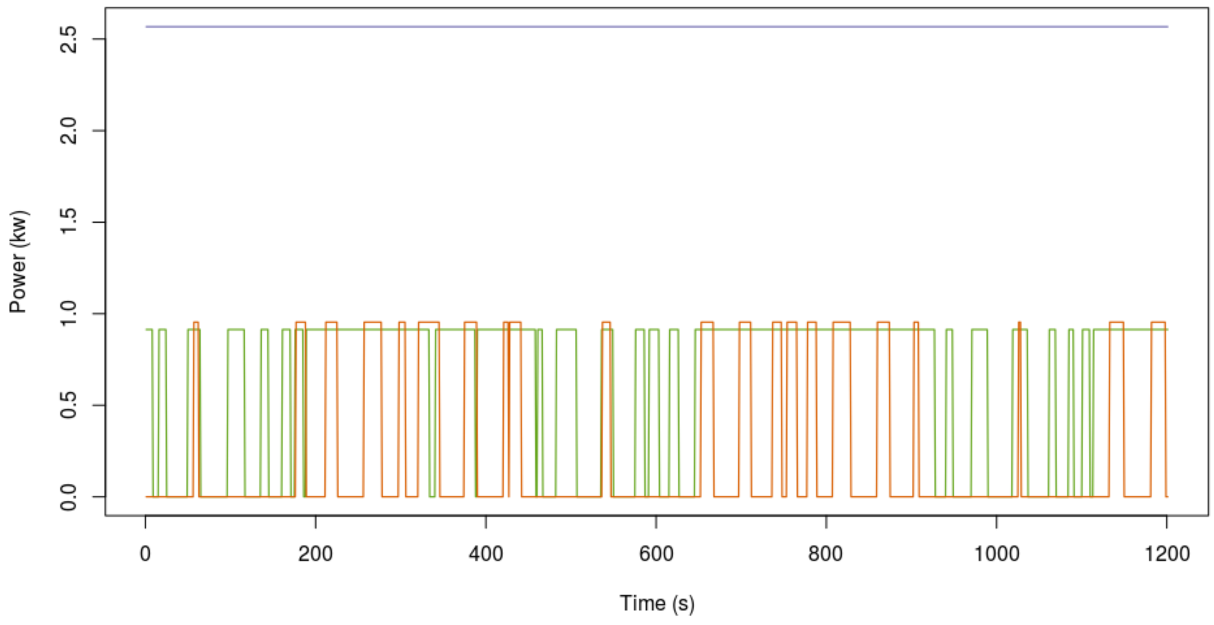

Figure 6.22. The NFHMM output of the 3 individual appliances in the Fortum household.

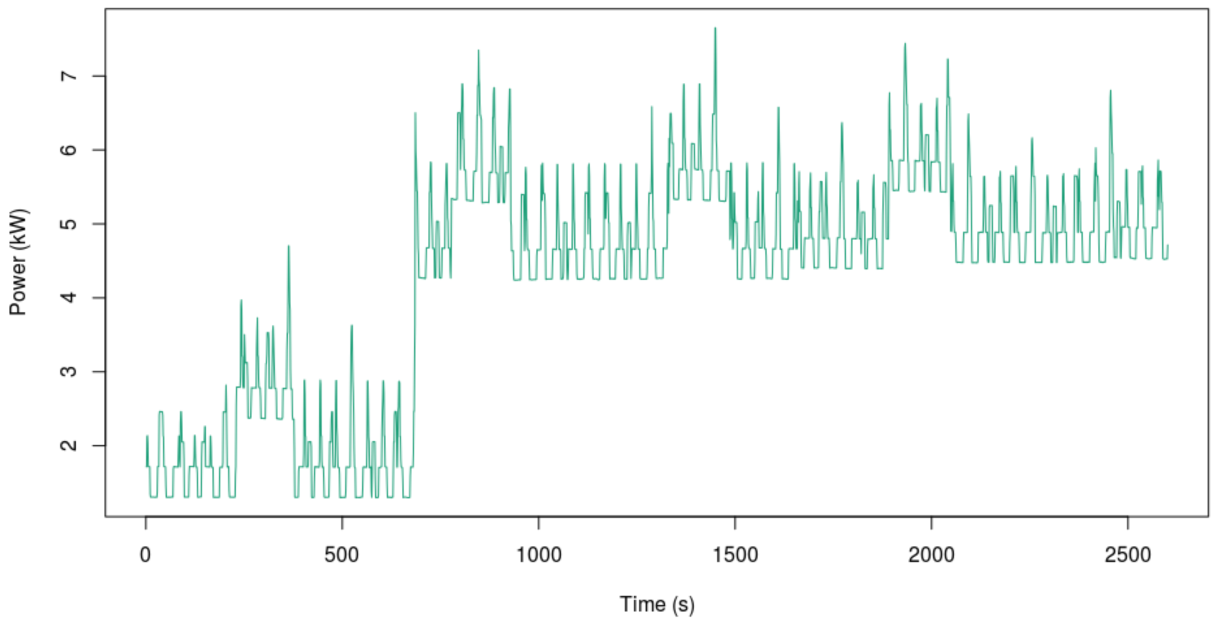

Figure 6.23. The Fortum pilot customer household electricity consumption containing a boiler switch-on event.

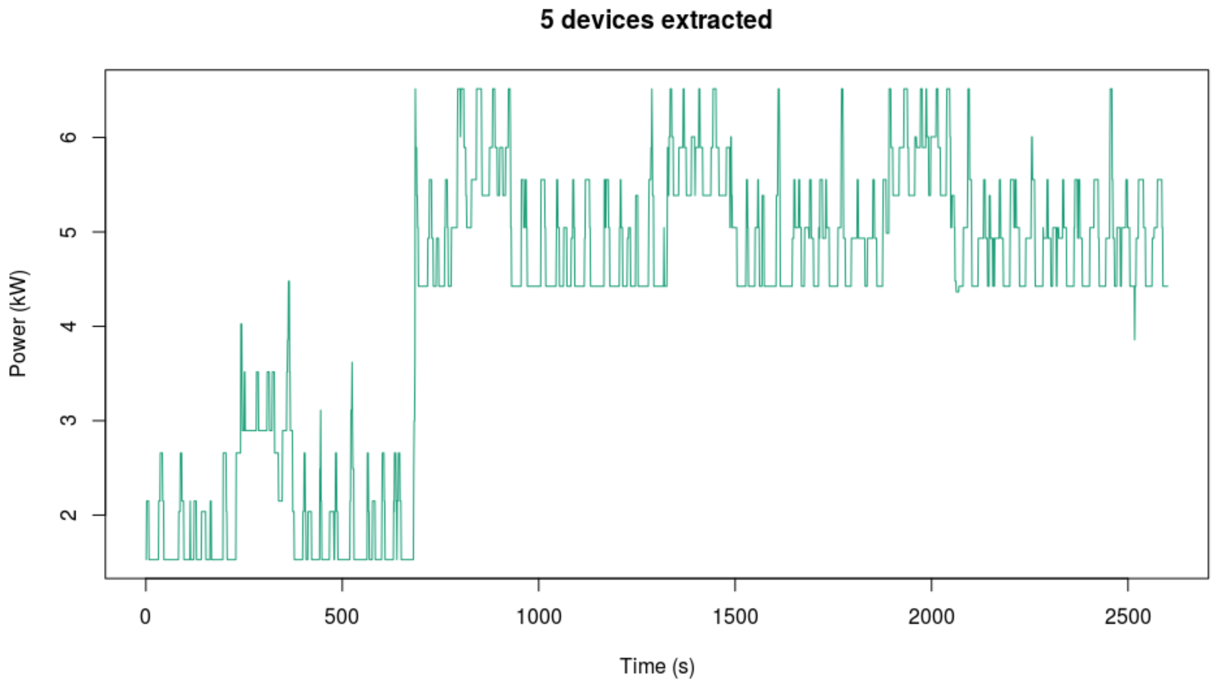

Figure 6.24. The NFHMM output aggregate electricity consumption signal for the Fortum household data containing a boiler switch-on event. The algorithm extracted 4 individual appliances in addition to the boiler.

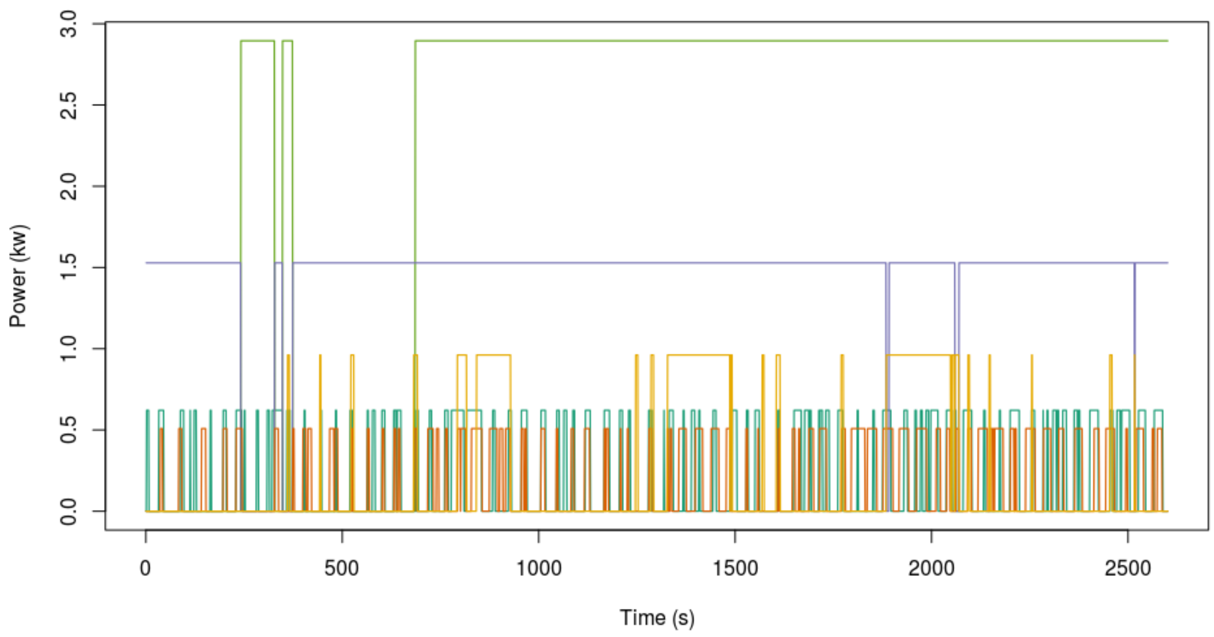

Figure 6.25. The NFHMM output of the individual components for the Fortum pilot customer household containing a boiler switch-on event.

7. Discussion

In this report, we provided a literature review of different NILM methods and a studied fully unsupervised NFHMM disaggregation algorithm introduced by Jia et al. (2015) in more detail. We examined shortly the performance of NFHMM algorithm and compared it to performance of some supervised algorithms implemented in NILMTK. Although it is difficult to compare the performance of unsupervised methods to that of supervised methods, it appeared that supervised methods outperformed clearly our implementation of NFHMM. For an unsupervised method our implementation of NFHMM performed well in some situations, but the frequently occurred convergence to local optima made it too unreliable to be operated as a disaggregation tool as such, which is mainly due to the limitations of the NFHMM model. Next, we discuss shortly how the implemented model could be improved without using labelled appliance-level training data from each household.

There is room for improvement in both the implementation as well as the used NFHMM model. There were some workarounds that we had to do because of limited time. Firstly, not all the hyperparameters were sampled from their correct posterior distributions. The conjugate priors were omitted and the likelihood functions were used as posterior distributions. Additionally, σ_ϵ was sampled with a heuristic as stated in Chapter 5. These workarounds might have affected the convergence of the algorithm and through that the disaggregation results and possibly better results would have been obtained using the correct posterior distributions.

Secondly, there were some problems using the `ars()` function of R that performs the ARS to a given log-concave function. The problems occurred when the initial points were chosen badly for certain function with certain bounds, which made the `ars()` function to do some infinite loops. There were also problems in satisfying the log-concavity requirement of the function, but this was caused by R's rounding errors of certain type of large sums which actually made the functions non-log-concave.

The third improvement for implementation would be applying the multi-state designation to NFHMM as in (Jia et al., 2015). This would consider appliances with multiple different states. However, this simple procedure was out of the scope of this report.

The NFHMM model itself could be improved as well. It seems that the NFHMM cannot find always the global optimum. The algorithm inevitably converges sometimes to local optima or alternatively, the global optimum is not reached after reasonable amount of iterations. The Markov assumption of NFHMM is a major limitation in the model: it assumes that the state of appliance depend only on the previous state. However, the appliances usually have their typical signatures which include the state durations. The boiler switch-on event detection in Chapter 6 is a clear example of this limitation. While the real boiler event is recognized correctly, NFHMM finds some excessive short-period boiler events before the real event, which are wrong and unreasonable. This behaviour could be avoided by adding a semi-markovian property to the model. The semi-markov property would consider the state durations of appliances, which would improve the disaggregation accuracy. The "mirroring" effect described in Chapter 6 would be suppressed as well by the semi-markov property.

In addition to the state durations, other features could be added to the model too. This could be done using approaches similar to CFHMM introduced by Kim et al. (2011). Most appliances have the typical time of day when used, so adding time of day as an additional feature could improve the accuracy. However, additional features make the model even more complicated which might make the algorithm slower.

One advantage of the Bayesian nonparametric property of NFHMM is that NFHMM finds the number of appliances adaptively so that the prior information of number of appliances is not required. Although NFHMM outperformed some other FHMM models using AIC or BIC as a criterion for the number of appliances in the publication by Jia et al., we thought that it would be useful sometimes that the user could set the number of appliances to the algorithm (2015). Then user could compare the disaggregation results of different number of appliances chosen as an argument. Our NFHMM implementation could be improved by at least adding upper bound to number of appliances so that NFHMM would not detect over 10 appliances. A large number of appliances in the model makes NFHMM quite slow and often it is not important to detect all small appliances.

The last problematic property of NFHMM that we found is that the power levels of appliances can be negative. Usually, this is not the case (unless there are batteries or solar panels in the household) and restricting the power levels to only positive values could be realistic. Namely, we noticed that our implementation of NFHMM produced negative power levels in some rare situations. This could be easily avoided by setting constraints to power level, but setting constraints affects convergence to optimal solution as well and in our experiments the convergence became worse after adding constraints.

The datasets used in our development and analysis in this project have been two very simple synthetic datasets. These datasets might not compare well with real world datasets but because performance level achieved by our implementation of the NFHMM algorithm is still relatively modest the characteristics of the data relative to the real world data in this stage is not essential. If more resources would have been available for this project and the performance of the algorithm was much improved, we would have proceeded to generate incrementally more complex and real world like synthetic datasets for testing. Eventually, we would have moved on to use highly submetered publicly available real world datasets for final refinement and tuning and validated the model with any adequately submetered data available from Fortum. The original unmetered datasets provided would have become the target of our focus only after these stages of refinement and validation would have been completed to high standards.

Regarding the performance comparison it must be again noted that the CO and FHMM implementations used in the NILMTK comparison had an unfair advantage at this testing phase. The datasets were perfect or near perfect and the data used for training and disaggregation were similar to an extent which is rare with real world data. Consequently, one should not conclude based on this comparison alone that the NFHMM algorithm or other unsupervised algorithms could not be improved and refined such as to be any match for the supervised algorithms. Collecting enough real world data from a wide enough variety of households and appliances to give supervised algorithms a clear advantage is costly. In addition, we believe that the NFHMM model could be developed to become semi-supervised and utilize any available submetered data or other relevant data regarding the target of disaggregation.

Due to the difficulty of reaching good results with the test data, we did not use many of the features that NILMTK had to offer. NILMTK would have been more useful had we been able to reach higher performance levels that would have inspired us to fully implement it using Python into NILMTK instead of just implementing a wrapper in order to conveniently test it with the various public datasets adapted for NILMTK. The statistical analysis and benchmarking functions implemented in NILMTK would have been more relevant at that phase.

Regarding the future, we believe Fortum should first study the commercial business potential of an imaginary high performing unsupervised disaggregation algorithms. If these seem attractive, then effort should be directed to further develop the algorithm as outlined earlier in this chapter. We believe that by following the path we outlined, it should be possible to reach much more promising results in about 400 hours of further research, and possibly even a performance level suitable for production with about another similar batch of work.

All in all, it seems that the disaggregation problem is certainly not trivial. The unsupervised methods have produced some promising results, but the performance is not yet comparable to performance of supervised methods. Supervised methods require the expensive training data, which in turn hampers their use. In the future, our implementation of NFHMM could be probably improved so that it would disaggregate the loads fairly well, however before committing to such a project, it should be evaluated whether developments in smart metering technology are likely to make it feasible to submeter a vast proportion of household appliances such as to make investing into a supervised approach more reasonable.

Bibliography

Altrabalsi, H., Stankovic, V., Liao, J., and Stankovic, L. (2016). “Low-complexity energy disaggregation using appliance load modelling”, AIMS Energy, vol. 4, pp. 884–905
`http://www.aimspress.com/article/10.3934/energy.2016.1.1`

Armel, C. K., Gupta A., Shrimali G., and Albert A.(2012). “Is disaggregation the holy grail of energy efficiency? The case of electricity”, Energy Policy
`http://dx.doi.org/10.1016/j.enpol.2012.08.062`

Baranski, M., and Voss, J. (2004). “Genetic algorithm for pattern detection in NIALM systems”, 2004 IEEE International Conference on Systems, Man and Cybernetics, 10–13 Oct 2004, The Hague, Netherlands
`https://doi.org/10.1109/ICSMC.2004.1400878`

Batra, N., Kelly, J., Parson, O., Dutta, H., Knottenbelt, W., Rogers, A., Singh, A. and Srivastava, M. (2014). “NILMTK: an open source toolkit for non-intrusive load monitoring”, Proceedings of the 5th international conference on Future energy systems
`https://arxiv.org/abs/1404.3878`

Farinaccio, L., and Zmeureanu, R. (1999). “Using a pattern recognition approach to disaggregate the total electricity consumption in a house into the major end-uses”, Energy and Buildings, vol. 30, no. 3, pp. 245–259
`https://doi.org/10.1016/S0378-7788(99)00007-9`

Ghahramani, Z., and Jordan, M. I. (1997). “Factorial Hidden Markov Models”, Machine Learning, vol. 29, pp. 245–273
`https://doi.org/10.1023/A:1007425814087`

Griffiths, T. L., and Ghahramani, Z. (2006). “Infinite latent feature models and the indian buffet process”, Advances in Neural Information Processing Systems, vol. 18, pp. 475–482
`http://mlg.eng.cam.ac.uk/zoubin/papers/ibp-nips05.pdf`

Hart, G. (1992). “Nonintrusive appliance load monitoring”, Proceedings of the IEEE, vol. 80, no. 122, pp. 1870–1891

Jia, R., Gao, Y., and Spanos, C. J. (2015). “A fully unsupervised non-intrusive load monitoring framework”, IEEE International Conference on Smart Grid Communications, 2–5 Nov 2015, Miami, FL, USA
`https://doi.org/10.1109/SmartGridComm.2015.7436411`

Johnson, M. J., and Willsky, A. (2012). “The Hierarchical Dirichlet Process Hidden Semi-Markov Model”, arXiv
`https://arxiv.org/abs/1203.3485`

Kim, H., Marwah, M., Arlitt, M., Lyon, G., and Han, J. (2011). “Unsupervised disaggregation of low frequency power measurements”, Proceedings of the SIAM International Conference on Data Mining
`http://dx.doi.org/10.1137/1.9781611972818.64`

Kolter, J. Z., and Jaakkola, T. (2012). “Approximate Inference in Additive Factorial HMMs with Application to Energy Disaggregation”, Proceedings of the Fifteenth International Conference on Artificial Intelligence and Statistics, vol. 22, pp. 1472–1482
`http://proceedings.mlr.press/v22/zico12/zico12.pdf`

Kolter, J. Z. and Johnson, M. J. (2011). “REDD: A public data set for energy disaggregation research”. Proceedings of 1st KDD Workshop on Data Mining Applications in Sustainability, San Diego, CA, USA.
`http://redd.csail.mit.edu/kolter-kddsust11.pdf`

Lange, H., and Bergés, M. (2016). “The Neural Energy Decoder: Energy Disaggregation by Combining Binary Subcomponents”, Proceedings of the 3rd International Workshop on Non-Intrusive Load Monitoring
`http://nilmworkshop.org/2016/proceedings/Paper_ID19.pdf`

Liao, J., Elafoudi, G., Stankovic, L., and Stankovic, V. (2014). “Power disaggregation for low-sampling rate data”, 2nd International Non-Intrusive Appliance Load Monitoring Workshop, Austin, TX, USA
`http://nilmworkshop.org/2014/proceedings/liao_power.pdf`

Onoda, T., Murata H., Ratsch, G., and Muller, K. (2002) “Experimental analysis of support vector machines with different kernels based on non-intrusive monitoring data”, Neural Networks, vol. 3, pp. 2186–2191

Parson, O., Ghosh, S., Weal, M., and Rogers, A. (2011). “Using Hidden Markov Models for iterative non-intrusive appliance monitoring”, Neural Information Processing Systems Workshop on Machine Learning for Sustainability
`http://eprints.soton.ac.uk/id/eprint/272990`

Parson, O., Ghosh, S., Weal, M., and Rogers, A. (2014). “An unsupervised training method for non-intrusive appliance load monitoring”, Artificial Intelligence, vol. 217, pp. 1–19
https://doi.org/10.1016/j.artint.2014.07.010

Prudenzi A. (2002). “A neuron nets based procedure for identifying domestic appliances pattern-of-use from energy recordings at meter panel”, IEEE Power Engineering Society Winter Meeting, 27–31 Jan 2002, New York, NY, USA
https://doi.org/10.1109/PESW.2002.985144

Roos, J., Lane, I., Botha E., and Hancke G. (1994). “Using neural networks for non-intrusive monitoring of industrial electrical loads”, Proceedings of the Instrumentation and Measurement Technology Conference, 10–12 May 1994, Hamamatsu, Japan
https://doi.org/10.1109/IMTC.1994.351862

Ruzzelli, A. G., Nicolas, C., Schoofs, A., and O’Hare, G. M. (2010). “Real-time recognition and profiling of appliances through a single electricity sensor”, 2010 7th Annual IEEE Communications Society Conference on Sensor Mesh and Ad Hoc Communications and Networks, 21–25 Jun 2010, Boston, MA, USA
https://doi.org/10.1109/SECON.2010.5508244

Suzuki, K., Inagaki, S., Suzuki, T., Nakamura, H., and Ito, K. (2008). “Nonintrusive appliance load monitoring based on integer programming”, SICE Annual Conference, 20–22 Aug 2008, Tokyo, Japan
https://doi.org/10.1109/SICE.2008.4655131

Teh, Y. W., Grür, D., and Ghahramani, Z. (2007). “Stick-breaking construction for the Indian buffet process”, Proceedings of the Eleventh International Conference on Artificial Intelligence and Statistics, vol. 2, pp. 556–563
http://proceedings.mlr.press/v2/teh07a/teh07a.pdf

Van Gael, J. (2011). “Bayesian Nonparametric Hidden Markov Models”, Doctoral dissertation, University of Cambridge

Zhao, B., Stankovic, L., and Stankovic, V. (2016). “On a training-less solution for non-intrusive appliance load monitoring using graph signal processing”, IEEE Access, vol. 4, pp. 1784–1799
https://doi.org/10.1109/ACCESS.2016.2557460

Zoha, A., Gluhak, A., Imran, M. A., and Rajasegarar S. (2012). “Non-intrusive load monitoring approaches for disaggregated energy sensing: A survey”, Sensors, vol. 12, 16838–16866
https://dx.doi.org/10.3390%2Fs121216838

Appendix A: Self-evaluation of project work

Herein we present a brief self-evaluation of our performance in the project. The first three paragraphs focus on our project related practices and project management. The following paragraph relates the realized effort against the allocated budget. Finally, the last two paragraphs describe the achievements we are especially satisfied of as well as the areas where we feel the project did not go as ideally as we would have hoped and provides some words of hindsight.

We employed few clear project management or teamwork practices. Because neither the client nor we understood nor were able to estimate the feasibility of the project, we decided to try to apply an incremental approach to how the goals and objectives of the project were formed. In addition to the fact that the project topic was outside both our and our client's know-how area, we had two further challenges. Firstly, only two of our team members were from the same department and knew each other in advance. This required us to explore how to best interact in order to maximize the productivity of the team. Secondly, all members were busy and had more or less long periods of travelling abroad during the course of the project which increased the difficulty of scheduling and coordination.

Consequently two more major decisions were made. First, it was decided that we try to book enough work sessions from all of our calendars as early as possible such as to ensure that we are able to follow our plans and do not have to work much individually. In addition to trying to work as much with the whole team in person, we also decided Mihail to be the project manager. This meant that he would carry out the scheduling and coordination work as well as lead the communication and interaction with other project stakeholders. Mihail was chosen primarily because he worked for Fortum already and was in the best position to perform in the role. The project manager also had a more leading role in opponent work as well as in all course related formalities. We tried to keep frequent enough contact with the client to ensure we share a similar understanding of project goals and are able to manage expectations.

Overall, we think our chosen practices worked fairly well. Thanks to the frequent live work sessions we were able to achieve progress almost every week and in the end we more than met the allocated work budget. Our work provided a good review and prototype that we believe will bring the client valuable insight into the problem we studied. Our team members were able to take initiatives on their own and the teamwork atmosphere was pleasant, constructive and fruitful without almost any pressure or direction from peers or the project manager.

The allocated effort for the project was 5 ECTS or 135 hours. Due to the good motivation levels among team members and our commitment to keep scheduling and contributing actively in live work sessions we were able to keep the pace of work good and steady. We believe most members contributed rather equally to the project. Over the duration of the whole course Samuel had used a tool to track his time use and the data indicates the following totals in hours for the months from Jan to May: 12, 35, 47, 29, 21. The total, 144 hours, slightly exceeds the course budget.

We believe that the project was successful in providing a case study of recent advances in electricity disaggregation methods. The project work serves as a useful reference for the client for developing further their vision on energy disaggregation services. NILMTK proved to be slightly too extensive for the scope of this project and would have been more useful had we had the resources to reach better results with the algorithm. We feel the implemented comparisons were somewhat unfair towards the unsupervised method, especially considering its tremendous practical advantages over the supervised ones. Given more resources, a more fair comparison scheme could have been devised. Thus, in retrospect, the effort put in to the use of NILMTK was more of a learning foray and demonstration than a direct contribution to our disaggregation method.

Nevertheless the implementation of both the algorithm in R as well as a wrapper for it along with all the dataset infrastructure for NILMTK was very interesting and we think we learned a lot. Although the implemented NFHMM model is not ready to be used for out-of-the-box disaggregation as such, we are satisfied by the implementation as a proof of concept for completely unsupervised electricity disaggregation, and believe that it lowers the threshold for the client to continue its development.