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SC@RUG 2016 proceedings

13th SC@RUG 2015-2016

Rein Smedinga, Michael Biehl and Femke Kramer (editors)

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About SC@RUG 2016

Introduction

SC@RUG (or student colloquium in full) is a course that master students in computing science follow in the first year of their master study at the University of Groningen.

SC@RUG was organized as a conference for the thirteenth time in the academic year 2015-2016. Students wrote a paper, participated in the review process, gave a presentation and chaired a session during the conference.

The organizers Rein Smedinga, Michael Biehl and Femke Kramer would like to thank all colleagues who cooperated in this SC@RUG by collecting sets of papers to be used by the students and by being an expert reviewer during the review process. They also would like to thank Agnes Engbersen for her very inspiring workshops on presentation techniques and speech skills.

Organizational matters

SC@RUG 2016 was organized as follows. Students were expected to work in teams of two. The student teams could choose between different sets of papers, that were made available through the digital learning environment of the university, *Nestor*. Each set of papers consisted of about three papers about the same subject (within Computing Science). Some sets of papers contained conflicting opinions. Students were instructed to write a survey paper about this subject including the different approaches in the given papers. The paper should compare the theory in each of the papers in the set and include their own conclusions about the subject. Of course, own research was encouraged.
This time no team proposed their own subject.

After submission of the papers, each student was assigned one paper to review using a standard review form. The staff member who had provided the set of papers was also asked to fill in such a form. Thus, each paper was reviewed three times (twice by peer reviewers and once by the expert reviewer). Each review form was made available to the authors of the paper through *Nestor*.

All papers could be rewritten and resubmitted, independent of the conclusions from the review. After resubmission each reviewer was asked to re-review the same paper and to conclude whether the paper had improved. Rereviewers could accept or reject a paper. All accepted papers[1] can be found in these proceedings.

In her lectures about communication in science, Femke Kramer explained how researchers communicate their findings during conferences by delivering a compelling storyline supported with cleverly designed images. Lectures on how to write a paper and on scientific integrity were given by Michael Biehl and a workshop on reviewing was offered by Femke Kramer.

Agnes Engbersen gave workshops on presentation techniques and speech skills that were very well appreciated by the participants. She used the 2 minute madness presentation as a starting point for improvements.

Rein Smedinga was the overall coordinator, took care of the administration and served as the main manager of *Nestor*.

Students were asked to give a short presentation halfway through the period. The aim of this so-called two-minute madness was to advertise the full presentation and at the same time offer the speakers the opportunity to practice speaking in front of an audience.

The conference itself was organized by the students themselves. In fact half of the group was asked to fully organize the day (i.e., prepare the time tables, invite people, look for sponsoring and a keynote speaker, etc.). The other half acted as a chair and discussion leader during one of the presentations. The audience graded both the presentation and the chairing and leading the discussion.

The gradings of the draft and final paper were weighted marks of the review of the corresponding staff member (50%) and the two students reviews (each 25%).

Students were graded on the writing process, the review process and on the presentation. Writing and rewriting counted for 35% (here we used the grades given by the reviewers), the review process itself for 15% and the presentation for 50% (including 10% for being a chair or discussion leader during the conference and another 10% for the 2 minute madness presentation). For the grading of the presentations we used the assessments from the audience and calculated the average of these.

In this edition of SC@RUG students were videotaped during their 2 minute madness presentation and during the conference itself using the video recording facilities of the University and with thanks to the CIT crew (special thanks to Adri Mathlener and colleagues for their help in this). The recordings were published on *Nestor* for self reflection.

On 7 April 2016, the actual conference took place. Each paper was presented by both authors. We had a total of 10 student presentations this day.

[1] except one, that did not meet the layout criteria and was not improved by the authors before the given deadline

Sponsoring

The student organizers invited one keynote speaker (Harry de Boer from Quintor). The corresponding company partly sponsored the event by providing lunch and coffee. The drinks at the end were sponsored by the Groningen Graduate School of Science. We are very grateful to

- Quintor Groningen
- Graduate school of Science Groningen

for sponsoring this event.

Thanks

We could not have achieved the ambitious goals of this course without the invaluable help of the following expert reviewers:

- Michael Biehl
- Doina Bucur
- Ilche Georgievski
- Jiri Kosinka
- Christian Manteuffel
- Arkario Pratama
- Brian Setz
- Ang Sha
- Alex Telea

and all other staff members who provided topics and provided sets of papers.
Also, the organizers would like to thank the *Graduate school of Science* for making it possible to publish these proceedings and sponsoring the awards for best presentations and best paper for this conference.
Rein Smedinga
Michael Biehl
Femke Kramer

Since the tenth SC@RUG in 2013 we added a new element: the awards for best presentation, best paper and best 2 minute madness. Therefore, from that edition on, we will have a Hall of Fame:

Best 2 minute madness presentation awards

2016
Michel Medema and Thomas Hoeksema
Implementing Human-Centered Design in Resource Management Systems

2015
Diederik Greveling and Michael LeKander
Comparing adaptive gradient descent learning rate methods

2014
Arjen Zijlstra and Marc Holterman
Tracking communities in dynamic social networks

2013
Robert Witte and Christiaan Arnoldus
Heterogeneous CPU-GPU task scheduling

Best presentation awards

2016
Sebastiaan van Loon and Jelle van Wezel
A Comparison of Two Methods for Accumulating Distance Metrics Used in Distance Based Classifiers

Michel Medema and Thomas Hoeksema
Providing Guidelines for Human-Centred Design in Resource Management Systems

2015
Diederik Greveling and Michael LeKander
Comparing adaptive gradient descent learning rate methods

Johannes Kruiger and Maarten Terpstra
Hooking up forces to produce aesthetically pleasing graph layouts

2014
Diederik Lemkes and Laurence de Jong
Pyschopathology network analysis

2013
Jelle Nauta and Sander Feringa
Image inpainting

Best paper awards

2016
Ynte Tijsma and Jeroen Brandsma
A Comparison of Context-Aware Power Management Systems

2015
Jasper de Boer and Mathieu Kalksma
Choosing between optical flow algorithms for UAV position change measurement

2014
Lukas de Boer and Jan Veldthuis
A review of seamless image cloning techniques

2013
Harm de Vries and Herbert Kruitbosch
Verification of SAX assumption: time series values are distributed normally

Contents

A Comparison of Two Methods for Accumulating Distance Metrics Used in Distance Based Classifiers

Jelle F. van Wezel and Sebastiaan J. van Loon

Abstract—Many pattern recognition problems deal with high-dimensional data. For instance, measurements from bio-molecular technologies often contain more than a thousand features. In such cases, classification based on non-statistical distance methods, such as Euclidean distance, are not accurate enough. One problem is that high-dimensional datasets often contain a lot of features which are hardly relevant to classification. Another problem is data containing features from different domains, making non-statistical distance methods an arbitrary measurement. By using distance measures based on statistical regularities in the data, classification accuracy can be significantly improved.

We compare two methods for accumulating distance metrics for use in distance based classifiers, *Supervised Variational Relevance Learning* (Suvrel) and *Global Metric Learning* (GML). Both methods construct a quadratic distance measure which weights dimensions and pairs of dimensions. This distance measure can be used to scale and rotate the feature space such that the classification will be more accurate. In GML a distance metric is obtained by minimizing the cost function using gradient descent. The Suvrel method specifies explicitly expression to obtain a distance metric, given the observed statistical properties of the data.

We evaluate the distance metrics obtained by both methods comparing: which features are most relevant, classification results, robustness, the number of parameters that need to be set, and overall usability. To do this both methods are implemented and used in combination with k-NN classification. The methods are tested using several datasets from the UCI machine learning repository. The results show that both methods greatly improve classification results when used in combination with k-nearest neighbor classification.

Index Terms—Classification, k-Nearest Neighbors, Gradient-Descent, Metric Learning, Suvrel, GML, Relevance Learning, Distance Metric, Feature Selection.

1 Introduction

The ease at which humans recognize patterns, such as a familiar voice or a face of a person they know is astonishing. Pattern recognition is one of the main aspects that characterize intelligent behavior. In the book *Pattern Classification* by Duda et al. this process is described as 'the act of taking in raw data and taking an action based on the "category" of the pattern' [3]. Pattern recognition is the sub-domain of machine learning which tries to automate the process of retrieving patterns from available data. It is used in many different fields which try to extract relevant information from data, ranging from medicine, where for example pattern recognition is used to help with diagnoses, to economics, where for example historical trends are examined to predict movements in the market [10].

As a special aspect, pattern classification entails the process of assigning a label to a new data point, based on some prior information. In general, classification compares some measurement between a new data point and known (labeled) data points, labeling the new data point with the most similar class. This process is based on the notion that data from the same class have similar features, a feature can be seen as a property a data point. When, for example, medical data is examined, different features can be height, weight, and gender. A data point x containing n features can be considered as a point in n-dimensional space: $x \in \mathbb{R}^n$.

The (dis)similarity between two points can be defined as the distance between those two points in the n-dimensional space. Points that lie closer to each other are considered more similar than further points. An often used distance measure is the Euclidean distance,

$$d_E(p,q) = \sqrt{(p_1-q_1)^2+\cdots+(p_2-q_n)^2}, \quad (1)$$

where $d_E(p,q)$ denotes the distance between two points p and q equation (1). Many pattern recognition problems deal with high-dimensional data i.e. data containing many features. For instance measurements from bimolecular datasets often contain more than hundreds of features, ranging from age and weight to hormone measurements. High dimensionality can cause problems when classification is performed. Due to the high number of features, it is often hard to distinguish between relevant and irrelevant features. Furthermore the differences in unit and scale between different features can cause problems when non-statistical distance methods such as the Euclidean distance metric from equation (1) are used. A better performance can be achieved by using the Mahalanobis distance. This distance metric is a generalization of the Euclidean distance that expresses the distance between two points as the number of standard deviations from the mean. Therefore it can be seen as a multi-dimensional z-score. The Mahalanobis distance between two points p and q is defined by:

$$d_M(p,q) = \sqrt{(p-q)^T M(p-q)}, \quad (2)$$

where M is the inverse covariance matrix of the dataset containing p and q. Note that the Mahalanobis distance with $M = I$ is equivalent to the Euclidean distance.

Using the Mahalanobis distance metric often results in a better classification then with non-statistical distance metrics. Performance can be further improved by using weighted distance metrics. Weighted distance metrics are similar to the Mahalanobis distance, but use a weight matrix W instead of the inverse covariance matrix for the data transformation. The goal of the weighted distance measure is to project the data to a space in which better classification can be achieved. This can be done by finding a matrix W which shrinks intraclass distances and stretches interclass distances. The distance measure using the weight matrix is given by:

$$d_W(p,q) = \sqrt{(p-q)^T W W^T (p-q)}. \quad (3)$$

Recently two new methods for accumulating a weighted distance metric W to be used in distance based classifiers have been proposed, *Global Metric Learning* (GML) and *Supervised Variational Metric Learning* (Suvrel). GML finds the matrix W by minimizing a cost function using gradient descent. This cost function punishes larger intraclass distances and small interclass distances. In Suvrel an explicit

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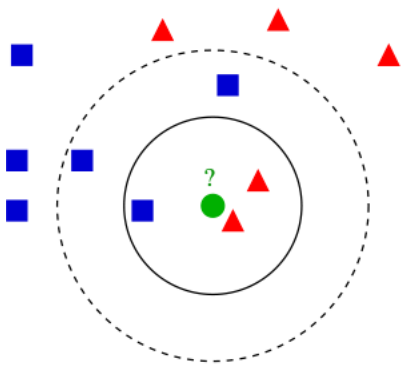

Fig. 1. k-NN for $k = 3$ indicated by the solid inner circle and $k = 5$ indicated by the dotted outer circle. The green circle will be classified as a triangle for $k = 3$ and as a square for $k = 5$. (Image by Antti Ajanki)

expression is given of a weight matrix which in theory should minimize the cost function [1, 5].

In this paper we compare the performance of both methods in terms of classification rate, speeds and efficiency. Both methods perform better than non-weighted distance metrics and we expect for both methods to achieve a comparable classification rate. Given that both methods perform similar in terms of classification, we expect the Suvrel method to outperform GML in terms of speed, efficiency and implementation.

In this paper we will first analyze both methods in section 3. In the next section we will discuss which data sets we will use for the validation of the two methods. In section 5 we will show how GML and Suvrel perform. Finally we will compare both methods in section 6 explaining the main differences between the two methods. The conclusion is given in section 7 as well as a outlook to possible feature work.

2 Background

In this section we will give a short overview of the different techniques used in pattern classification.

2.1 K-Nearest Neighbor Classification

k-nearest neighbor (k-NN) is one of the simpler algorithms for classification which allows for non-linear classification. It is therefore widely used in machine learning. The algorithm classifies a presented data point by evaluating the distance to the k nearest known data points. If a majority of the neighboring data points is from a certain class, k-NN will classify the presented data point as this majority. When k is even a tie can occur, consequently a tie breaker must be implemented in case of even k.

In figure 1 the concept of k-NN is illustrated for $k = 3$ and $k = 5$. In this figure the green circle will be classified as a triangle for $k = 3$ and as a square for $k = 5$.

2.2 Learning Vector Quantization

A drawback of k-NN is that in order to classify a new data point, all previously known data points must be evaluated to find the nearest neighbor(s). A solution to this problem can be found by replacing groups of similar points by one prototype. These prototypes represent a cluster of data points, greatly reducing the size of the number of points that are compared when a new point is classified. In order to classify new data, a point has only to be compared to these prototypes which greatly reduces computing time.

In order to yield accurate classification results with the use of prototypes, an appropriate prototyping method must be chosen. Which method is suitable depends greatly on the 'shapes' of the clusters in the dataset and the dimensionality of the data. A few examples of prototyping methods are K-means [8], Neural Gas [9], and Learning Vector Quantization (LVQ) [6]. LVQ offers a heuristic which optimizes the position of labeled prototypes for a dataset. Prototypes are updated by comparing the label of data points to the closest prototype. If the label of the prototype and the data point are the same, the prototype is moved in the direction of the data point with an appropriate step size. The prototype is moved away if the labels do not match. The update rule is defined by:

$$\vec{w_j}^* = \vec{w_j} \pm \eta(\vec{x_i} - \vec{w_j}), \tag{4}$$

where $\vec{w_j}^*$ is the newly updated prototype, $\vec{w_j}$ is the prototype closest to data point $\vec{x_j}$. The sign of the term depends on the similarity of the labels.

2.3 Feature Scaling

Since the introduction of LVQ in 1986 [6] many variances on this method have emerged which try to improve on the method by scaling data dimensions to achieve a better classification rate. A few of these methods are listed below. RLVQ [2] uses feature weights to make more important features more prominent. It does this by assigning weights to the features and updating these weights during the learning process. GRLVQ [4] is an improvement on RLVQ, where the training is given as a stochastic gradient descent on an appropriate error function. GMLVQ [12] improves even further on RLVQ by introducing a full matrix that takes the correlations between the different features in account. Data points are scaled using the relevance matrix when distances are calculated. During the learning step both the prototype and matrix are updated corresponding to the similarity between the prototype and the point.

The methods we compare in this paper accumulate a matrix to better differentiate between the importance of features, and combinations between features present in a dataset, in order to find better clustering and classification results. This way of influencing the distance metric by a matrix based the correlation between features in data can also be found in the GMLVQ method. The goal of the by us evaluated methods is to find this matrix independent of a classification algorithm. By finding the weight matrix independent of the learning step, it is possible to use different classification methods with the same weight matrix. As an added benefit, simple classification methods can be used while still achieving good classification results.

3 Methods

In this section we describe how the GML and Suvrel methods determine weight matrices to be used in distance measures.

3.1 Global Metric Learning (GML)

In the introduction is explained how a weighted distance metric d_W can be used to improve classification. The paper 'Global Metric Learning by Gradient Descent' by Hocke and Martinetz proposes a method for the accumulation of a matrix W to be used in such a distance metric. This matrix can be used in the calculation of the distances using a quadratic form similair to equation (2) and equation (3).

The distance in this space is expressed as:

$$d(x_i, x_j) = ||W^T x_i - W^T x_j|| = ||x_i - x_j||_W^T, \tag{5}$$

where x_i and x_j are two arbitrarily chosen data points. In order to project the data points $x_i \in R^n$ to a m dimensional space the matrix W is expressed as:

$$W = (w_1, ..., w_n) \in R^{n \times m}. \tag{6}$$

A classifier needs to be able to distinguish between data points in the same class and data points in different classes. The data points are labeled with the label $y_1, ..., y_n$ where n is the number of classes. In order to improve classification it is favorable to increase the interclass distances and decrease the intraclass distances. To achieve this the data is distributed into the two sets D (Different) and S (Same), with:

$$D = \{(x_i, x_j) : y_i \neq y_j\}, \tag{7}$$

$$S = \{(x_i, x_j) : y_i = y_j\}. \tag{8}$$

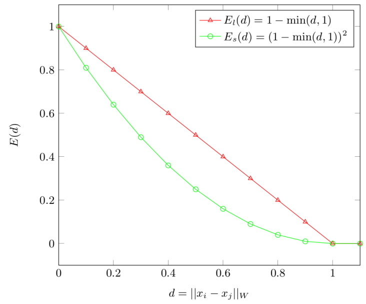

Fig. 2. Linear and exponential cost function comparison. E_l is the linear cost function and has a constant gradient. This means all the interclass pairs (far or close) influence the energy the same. The non-linear function E_s punishes close by pairs more than far apart pairs. (Image taken from [5])

The set D contains all the tuples of data points with different classes and the set S contains the tuples of data points within the same classes.

In GML the gradient descent algorithm uses the derivative of an energy function to determine how to influence a weight matrix in order to minimize the energy. In the context of distances, the energy function is given by the sum of the distances between intraclass and interclass pairs. The function is minimized by repeatedly calculating the gradient and updating the weight matrix until convergence is reached. The energy function E for GML is defined as:

$$E(W) = \alpha \sum_{(i,j)\in D} (1 - \min(||x_i - x_j||_W, 1))^2 + (1-\alpha) \sum_{(i,j)\in S} ||x_i - x_j||_W^2, \tag{9}$$

where α is between zero and one and indicates the ratio between the respective weights for the inner- and intraclass distances. This energy function uses the distance metric $||x_i - x_j||_W^T$ as given in equation (5).

The energy function consists of two summation terms, the left term sums over all the tuples in the set D. Because gradient descent minimizes the energy function we want to penalize pairs with small distances. However, we want to see that pairs that are close together are penalized more than pairs that already have some distance between them. In figure 2 the squared error term is compared to a linear term. The $\min(d,1)$ function takes the minimum between the distance and 1. Since distances higher than 1 will influence the energy function negatively while the opposite effect is desired. The cut-off value 1 is taken from the GML paper.

The right term sums over the set S. This set contains all the tuples in the same class and punishes large distances between the points and encourages small distances. The gradient for the weight vectors w_k in W can be obtained by the derivative of the energy function equation (9). This function is given by:

$$\frac{\delta E(W)}{\delta w_k} = -2\alpha \sum_{(i,j)\in D} \frac{(1 - \min(||x_i - x_j||_W^T, 1))}{||x_i - x_j||_W^T} (w_k^T (x_i - x_j))(x_i - x_j) + 2(1-\alpha) \sum_{(i,j)\in S} (w_k^T (x_i - x_j))(x_i - x_j). \tag{10}$$

The gradient for the weight vectors shows us in which direction and how much the individual vectors should be altered to reach a local minimum. By altering the weight, the energy function will be minimized giving us the optimal matrix W for the dataset.

3.2 Supervised Vector Relevance Learning (Suvrel)

In the paper 'Supervised Variational Relevance Learning, an analytic geometric feature selection with applications to omic datasets' [1] the authors propose a method which gives a direct expression for a weight matrix W to be used in a weighted distance metric given in equation (3) in the introduction. Similar to GML, Suvrel defines a weight matrix which incorporates the significance of each feature. This is done by shrinking non relevant dimensions and stretching relevant ones. Features are considered to be relevant if they contribute to large interclass distances or small intraclass distances.

The Suvrel method differs from the GML giving an explicit expression for which W can be obtained. The cost function to be minimized by W is similar to that of GML given in equation (9) and is given by:

$$E(W) = \sum_{i,j\in S} \langle d_W(i,j) - \lambda \sum_{i,j\in D} \langle d_W(i,j), \tag{11}$$

where D denotes the set of tuples of interclass pairs and S denotes the tuples of intraclass pairs. The angle brackets denote an average of the distances between all elements of a class using the weighted distance measure. The parameter λ denotes the weight of the distances between interclass distances. Looking at the cost function we can see that $\sum_{i,j\in S} \langle d_W(i,j)$ is the sum of the (weighted) intraclass distances and $\sum_{i,j\in D} \langle d_W(i,j)$ is the sum of the average (weighted) interclass distances for each pair of classes.

The weighted distance is the summation over all distances for each pair of classes, we can therefore express the cost function as such:

$$E(W) = \sum_{(\mu,\nu)\in F} W_{\mu\nu} \varepsilon_{\mu\nu}, \tag{12}$$

where μ and ν denote a pair from the set of features and $W_{\mu\nu}$ denotes the element from the weight matrix for those features, $\varepsilon_{\mu\nu}$ is given by

$$\varepsilon_{\mu\nu} = \varepsilon_{\mu\nu}^{in} - \lambda \varepsilon_{\mu\nu}^{out}. \tag{13}$$

In equation (13) the error function is expressed as a combination of two functions, $\varepsilon_{\mu\nu}^{in}$ corresponding to the cost of the intraclass distances and $\varepsilon_{\mu\nu}^{out}$ corresponding to the cost of the interclass distances. In the paper the authors show that this cost function can be expressed as a combination of the sum of covariance matrices for each class and the covariances of the feature means of the classes.

$$\varepsilon_{\mu\nu} = [2 - (K-1)\lambda] \sum_{a\in C} \text{cov}(x_\mu^a, x_\nu^a) - \lambda K^2 \text{cov}(m_\mu, m_\nu), \tag{14}$$

where K is the number of classes in the dataset, x_n^a denotes the set of samples of the n^{th} feature of class a, (x_μ^a, x_ν^a) denotes the covariance matrix between two features of a class and $\text{cov}(m_\mu, m_\nu)$ is the covariance between the vector of feature means for each class.

Looking at equation (14) we see that the cost function increases when there is a higher variance in the intraclass features and decreases when there is a higher variance between the feature means of different classes. This can be understood intuitively when comparing the probability of two classes overlapping. When the variance of a feature in a class is high, the data points in a class will have a higher spread increasing the change of overlapping with another class. Likewise will a high variance between the feature means of different classes indicate that there is a higher difference is the mean feature values in the class, there is a larger spread between data point of different classes resulting in a smaller probability of overlap.

The authors show that the cost function can be minimized directly, given the analytic solution equation (15)

$$W = \frac{-\varepsilon_{\mu\nu}}{\sqrt{\sum_{\mu'\nu'} \varepsilon_{\mu'\nu'}^2}}. \tag{15}$$

4 Data and Experiment

In this section the used datasets are discussed, as well as the experimental methods used to quantify both methods.

4.1 Data

To compare the classification performance of k-NN in combination with GML and Suvrel, multiple datasets from the open UCI machine learning repository are used [7]. To observe the influence on the classification quality of the number of features in the data, the chosen datasets cover a range of dimensions. Distinction is also made between the number of classes in the data. Care is taken to make sure the datasets do not contain missing values, since dealing with missing values is outside of the scope of this project. No further preprocessing is done on the data.

Table 1. Properties of the datasets.

Name	Samples	Dimensions	Classes
Breast Cancer	683	10	2
Parkinsons	195	22	2
Iris	150	4	3
Balance Scale	625	4	3
Seeds	210	7	3
Wine	178	13	3

4.2 Experiment

In line with [5], 3-nearest neighbor classification is performed on the datasets described in section 4.1. Since we only want to compare the relative differences in results the optimal number of neighbors is less relevant for this project. For validation of the classification results 10-fold cross-validation is used. Every iteration the data-sets is split into 50% training data and 50% test data, using the same split as used in the GML paper.

To easily compare the quality of classification for the different distance scalings, we use the percentages of misclassified data points as evaluation metric. To put the classification results into broader context, all data is also classified using Euclidean distances.

The GML method has a parameter α which denotes the ratio between the inter- and intraclass distances in the energy function given in equation (9). During the experiment this value is set to 0.9 for all datasets. This is the same value as is used in the GML paper.

5 Results

In this section we present the classification results that are obtained with k-NN, when the data is scaled using the correlation matrix obtained by GML and Suvrel.

5.1 Classification Results

The classification results are given in table 2 for k-nearest neighbor classification using the GML and Suvrel distance metrics as well as the Euclidean distance. Unfortunately, due to the long execution time of gradient descent and because our gradient descent algorithm was not very sophisticated, finding the right parameters for the learning rate and number of iterations turned out to be a very slow process. Due to time constraints we were not able to find the right parameter for all datasets. However, when the right parameters were found, the classification results where very close to those given in the GML paper. We have therefore chosen to complement the found results with those in [5]. This way it is still possible to compare the classification results between GML and Suvrel for all chosen datasets. The result taken from the paper are marked with an asterisk in table 2.

5.2 Feature Weights

Besides the classification results, the GML and Suvrel method can also be compared by looking at their respective weight matrices. The weight matrix indicates which features are most discriminating for classification. In figures 3 to 5 the normalized weights are displayed for each independent feature for both GML and Suvrel. These elements are taken from the diagonals of the weight matrices.

Table 2. Classification mean error rates and standard deviation. The error rates taken from the paper from GML are marked with an asterisk.

	Euclidean		GML		Suvrel	
Dataset	Mean	SD	Mean	SD	Mean	SD
Breast Cancer	39.28	2.92	*3.68	*0.68	**2.96**	**0.81**
Parkinson	17.61	3.88	*10.10	*4.04	**10.18**	**3.57**
Iris	4.93	2.67	**2.80**	**1.60**	2.93	1.86
Balance Scale	18.01	1.59	**9.60**	**1.55**	16.61	2.24
Seeds	10.38	2.56	**6.00**	**1.35**	8.48	2.00
Wine	29.66	2.44	***2.89**	***1.75**	4.27	2.53

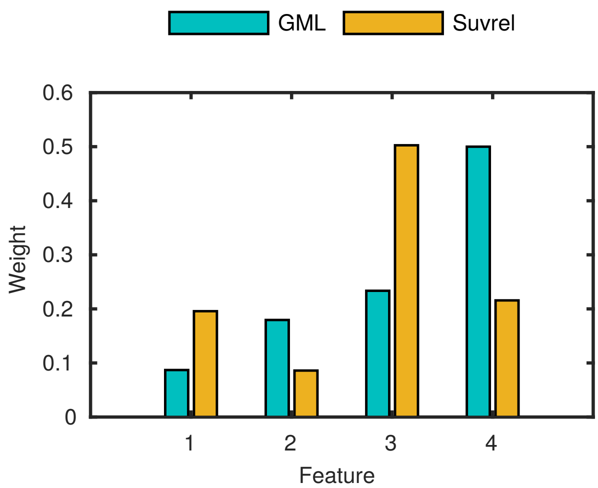

Fig. 3. Feature weights for the iris dataset as given by the diagonal elements of the (normalized) WW^T.

6 Discussion

In this section we will discuss the results given in the previous section. We compare GML and Suvrel in terms of by evaluating the quantitative result as well as by comparing the weight matrices found by the methods. Furthermore we compare both methods by looking at their usability.

6.1 Quality of Classification

In section 5, table 2 the classification errors are given. Looking at the results we see that both methods perform much better when compared with the standard Euclidean distance metric. When comparing the results between the two methods, we see that for binary datasets the performance of both methods is very similar, with a small lead for Suvrel. For datasets containing more than three classes the GML method outperforms Suvrel with quite a higher margin. However, Suvrel still outperforms classification using a Euclidean distances by a large margin. When we compare the found classification result of our GML implementation, with the classification results listed in the paper, we see the classification results are about the same. The few discrepancies between the results can be accounted for by the random factor that is introduced by cross-validation.

6.2 Comparison of Weight Matrices

In figure 3 to 5 the accumulated weight for each feature in the dataset is given. When we look at the results of the Iris and Seeds dataset we see a surprising result. The weights found for each feature differ a lot between the two methods. When looking at the results of Suvrel we see a lot of differences between the weight of each feature, while for GML the weights are often closer together. However, when we look at the classification results in table 2 for the iris dataset, we see that a

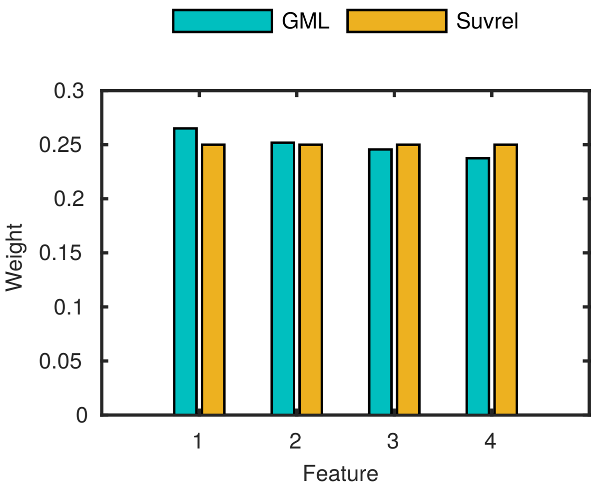

Fig. 4. Feature weights for the balance dataset as given by the diagonal elements of the (normalized) WW^T.

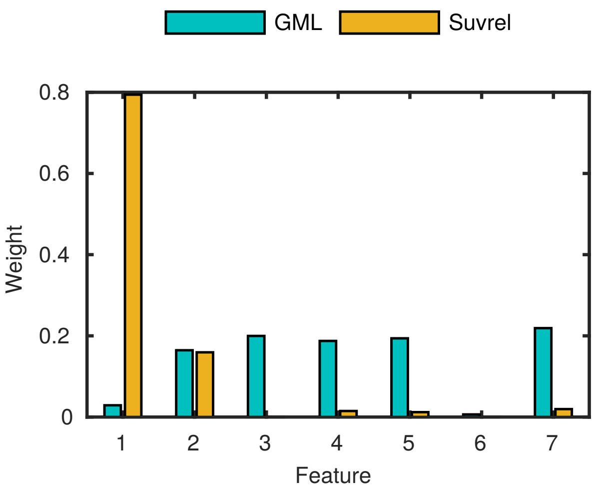

Fig. 5. Feature weights for the seeds dataset as given by the diagonal elements of the (normalized) WW^T.

difference in the weight matrix does not necessarily has to result in a big difference in the classification result. This could indicate multiple (sub-) optimal weight matrices exists.

6.3 Usability

In this section we will evaluate both method in terms of usability and execution time. When looking at the usability of GML and Suvrel there is a distinct winner. The Suvrel method is quite easy to implement and has a very short execution time. Furthermore is the usability high since there is only one parameter that needs to be adjusted.

In terms of usability GML does not perform well. Due to the nature of gradient descent, execution times can be very long especially when high-dimensional datasets are processed. Furthermore, GML is very sensitive to which value are set for the parameters. It is difficult to find the right parameters for gradient decent which results in an acceptable minimum. When wrong parameters (such as a too high learning rate) are used, the gradient descent algorithm can overshoot the minimum, causing the quality of classification to decline giving sometimes worse performances than Euclidean distance. This makes GML not very robust for parameter changes.

To counter the long execution times mini-batch gradient descent and stochastic gradient descent were tried as alternative methods. By using these methods the running time can be reduced. However this also decreases the quality of classification. The original paper that proposed GML used an automated way of finding the learning rate, one of the parameters, based on the data. This method proposed by Schaul et al. [11] finds the learning rate by evaluating the data-set and could improve the usability of GML.

7 Conclusion

In this paper we have studied two methods of accumulating a correlation matrix to be used in scaled distance metrics. We have tested both methods using different datasets. We have shown that with both methods classification results can be greatly improved, with a slight edge for GML for datasets containing more than two classes. In terms of usability and robustness we have seen that Suvrel outperforms GML in all cases.

Comparing the accumulated distance matrices we observed that, while both methods try to optimize the weight matrix to achieve better classification, the resulting weight matrices differ a lot between the two methods.

7.1 Future Work

In this paper we evaluated GML and Suvrel for accumulating weight matrices and tested them with k-NN classification. This works well for comparing the two methods, but does not tell us how the matrices perform when other classification methods are used. It would be interesting to see how the different matrices perform with for example a neural-gas or LVQ algorithm and if the gain in the quality of classification is consistent between different classification methods. This might tell us more about the applicability and viability of GML and Suvrel.

The data sets used in this project were deliberately selected to not have any missing features or noise, a luxury sparsely found in real world application. It would be informative to see how the two methods compare when confronted with defects present in the data.

The original GML paper used the parameter $\alpha = 0.9$. This parameter pushes intra class data points further apart and inner class data point closer together, as described in section 3.1. We took this parameter and did not alter it. Variation in this parameter might yield different and better results for different types of data. Further research is needed to find the effects of the alteration of this parameter.

The Suvrel method clearly outperformed the GML method in terms of speed. It also outperformed GML in case of the binary classes as can be seen in table 2. If Suvrel could be improved to also outperform or match GML performance for datasets containing more than two classes, it would be the better algorithm in our comparison. Because Suvrel outperformed the GML in terms of speed it would be interesting to see what happens when a matrix produced by Suvrel is used for the initialization of GML.

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Embedding Software Architecture Evaluation Methods in Extreme Programming: A New Approach

Firat Sertgoz, Eric Rwemigabo

Abstract—Agile development methods, have been receiving increased attention over the past decade. They try to satisfy customer, adapt to changes, release in less time with reduced costs. One of the most popular methods is XP. Even though XP offers a light-weight process, it does not have tools and methods to evaluate architecture of a system. Software Architecture Evaluation Methods, are methods and tools that help individuals to analyse software architecture of a system. With an increase interest in XP, studies have been done on how to embed several Software Architecture Evaluation Methods into XP. Our research presents a description and comparison of three embeddings of SAEMs into Extreme Programming. Two of these were written in reference to previous work and done by combining different Architecture Evaluation methods and XP. The third approach on embedding Architecture Evaluation method is proposed by us, which is embedding DCAR into XP.

Index Terms—Software Architecture Evaluation Methods, Agile Architecture, Extreme Programming

1 Introduction

With the rapid development of new technologies, continuous change of customer needs, time to market, new ways which adapt to these needs have emerged in the field of software development. Fast-paced, reactive and flexible approaches to software development have been grouped under the name of Agile methods. These methods have been increasingly used and discussed in the software industry since the release of the Agile Manifesto [13] [8]. Companies and projects of different sizes seem to adopt these methods because of the prone to flexibility of these methods [3]. Abrahamsson et al. [1] lists the common characteristics of agile methods as; "iterative and incremental life cycles, focus on small releases, collocated teams, and a planning strategy based on a release plan driven by a feature or product backlog and an iteration plan handling a task backlog." Today, some of the well known agile methods are FDD (Feature-Driven Development), XP (Extreme Programming), SCRUM and Crystal methods.

Buschmann et al. [5], discuss a definition for software architecture and come to a conclusion that it does not have a specific definition rather it can be a cross section of decisions, from a handwritten sketch down to critical details, some of which are properly and explicitly acknowledged as decisions, some of which are assumptions or givens, and some of which are decisions that are made unintentionally and recognized as significant only in hindsight. According to this discussion it is possible to say that every system with a reasonable scale that includes interactive components will have an architecture. Even though agile methods propose light-weight and reactive solutions to software development, they often neglect the process of evaluating the architecture of a system due to the heavy-weight documentation burden that it brings with it. Evaluation of a system's architecture, even if it emerged by Refactoring [6] or was designed up-front, is an important process for analysing the non-functional requirements, quality attributes, decisions and their relations.

For evaluation of system's software architectures, software architecture evaluation methods (SAEM) are offered. Some of these methods which we will discuss favour heavy documentation and are time consuming and not suitable for agile methods that we have named. Thus, embedding these methods into agile methods requires hybrid approaches or changes in these SAEMs.

In our research we will be reviewing primary studies that embed certain SAEMs into XP, as it is one of the most studied agile methods according to Yang et al. [18]. We will also offer a new way to combine XP with a SAEM. Finallly, we will compare the embedded versions of SAEMs and our embedding method according to criteria which were driven from agile approaches and agile manifesto. Several comparisons of SAEMs have been conducted before, an addition of an in-depth comparison of these evaluation methods when they are embedded into agile methods would enhance these studies. We believe that this research would help agile methods users to have an overview of what are the current SAEMs that could be embedded into agile methods, how they are embedded, what would be a suitable method when they want to use it in their own systems and introduce them to a new embedding strategy.

The rest of this paper is as follows: section 2 defines the methodology that we used to compare the embedded versions of SAEMs into agile methods, section 3 presents brief descriptions of SAEMs, section 4 provides descriptions of XP, section 5 shows how certain SAEMs are embedded in XP, section 6 introduces a new strategy for embedding a SAEM in XP and section 7 provides a comparison of the embedded SAEMs and section 8 concludes the research.

2 Methodology

The guideline that we used when comparing the embedded SAEMs is proposed by Sharifloo et al. [16]. There are 9 criteria; individual and interaction, documentation, customer collaboration, responding to changes, simplicity, feedback, time overhead, cost overhead, quality improvement. Each criterion are derived according to the Agile Manifesto's criteria which are: individuals and interactions, customer collaboration, responding to changes and documentation.

3 Software Architecture Evaluation Methods

In software Architecture Evaluation, we have come across multiple scenario-based methods and a few decision-centric method.
Scenarios according to Rick Kazman et al[9] provide brief narratives of expected or anticipated system uses from both user and developer views-provide a look at how the system satisfies quality attributes in various use contexts. This is what the scenario-based methods are based on. Decision-centric can be defined in the sense that the evaluation starts when stakeholders (with the review teams assistance) select a set of decisions to analyze in the context of relevant project and company-specific decision forces[17].

3.1 Architectural Trade-off Analysis Method (ATAM)

Architectural Trade-off Analysis Method introduced by Kazman et al. [10] is a scenario-based software architecture evaluation method that includes 6 steps. ATAM assumes that each quality attribute has connections with other attributes through specific architectural elements. It aims to analyse the relationships between architectural elements and

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Criterion	Explanation
Individual and Interaction	Here, we shall have a look at the interactions of the individuals in the embedding of each method in terms of who interact in the particular method, and how often they do so.
Documen-tation	In this comparison, we look at what documentation is required, the amount of documentation required, and it's application in each embedding.
Customer Collabora-tion	In this comparison, we look at which ones the customer's participation is required.
Respond-ing to changes	Here, we compare the response in terms of architectural analysis after changes have been made in the Architecture.
Simplicity	This compares the skill level and amount of experience needed to take part in the sessions of the embeddings.
Feedback	Compares the level of feedback provided and/or who provides this feedback.
Time Overhead	Compares the how much time the embeddings take and whether this time can be measured.
Cost Overhead	This will compare the aspect of cost by considering which embedding will require more technical staff depending on the skill required to perform certain roles in an embedding.
Quality Im-provement	This compares how the embeddings improve the quality of the architecture.

Table 1

come up with dependencies of the components. These are called trade-off points. For example a system might have a performance requirement in terms of latency. This requirement depends on the architectural elements such as the policy for allocating processes to processors, scheduling concurrences, managing access. The architect should have trade-offs between these architectural elements in order to satisfy the mentioned quality attribute.

The methods is divided into four areas namely; scenario and requirements gathering, architectural views and scenario realization, model building and analysis, and trade-offs. The general road-map for this method is as such; once the initial scenarios and requirements are gathered and initial architecture is introduced, each quality attribute is evaluated in isolation. After individual evaluations, the trade-off points are found. After analysis of these trade-off points the architecture can be refined or the requirements may be changed.

The steps involved in this road-map are:

1. **Collect Scenarios**
2. **Collect Requirements/Constraints/Environment**
3. **Describe Architectural Views**
4. **Attribute-Specific Analyses**
5. **Identify Sensitivities**
6. **Identify Trade-offs**

The steps illustrated into the road-map are seen in the Figure 1.

3.2 Cost and Benefit Analysis Method (CBAM)

The Carnegie Mellon Software Engineering Institute (SEI) has come up with a number of architecture-centric methods and CBAM is one

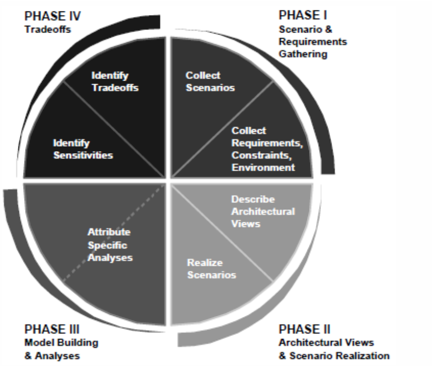

Fig. 1: Mapping of ATAM steps into the road-map. [10]

of these method. According to SEI [14], CBAM is an architecture-centric method for analyzing the costs, benefits, and schedule implications of architectural decisions. It builds on ATAM but is not an absolute prerequisite. CBAM is benefitial to the users in a way that it helps them make informed decisions about software requirements, and investments. It can be implemented by following these steps:

1. Choosing scenarios and architectural strategies.
2. Assessing quality attribute benefits.
3. Quantifying the benefits of architectural strategies.
4. Quantifying the costs and schedule implications of architectural strategies.
5. Calculating desirability
6. Making decisions

3.3 Decision-Centric Architecture Reviews (DCAR)

Most of the software evaluation methods that are used in the industry are scenario-based which test software architectures against scenarios that satisfy a systems major quality requirements. A method offered by van Heesch et al. [17], rather defines a method which uses decision forces to evaluate the software architecture of the system. Decision forces are the influences that effect the software architect looking for a solution for an architectural problem. Examples to these decision forces may be listed as constraints, risks, political or organisational considerations, personal preferences, experience and business goals and time to market. All of these decision forces have a direction and a magnitude. Some forces may either be in different directions or they can be orthogonal. To make the best possible decision an architect must balance all of the forces. These forces are mutable, meaning that according to the changing company evolution, tactical orientation and emerging new technologies the forces direction and magnitude could change.

DCAR uses these forces to evaluate the software architecture. It requires a lead architect and one or two members from the development team. An addition to them, a representative of management and customer perspective should also be included. Reviewers who are also involved should have knowledge on software architecture design. The following steps are taken for DCAR:

1. **Preparation**, where the participants study the potential architecture decisions and decision forces
2. **Introduction to DCAR**
3. **Management Presentation**, management gives a brief presentation to express the business related decision forces to consider.
4. **Architecture Presentation**, lead architect introduces the architecture to all DCAR participants.

5. **Forces and Decision Completion**, reviewers clarify the architecture decisions and their relations. A collaborative session takes place where all of the participants get a good understanding of the achitectural decisions. A diagram of decision relationships are formed.

6. **Decision Prioritisation**, stakeholders negotiate which decisions to review. Voting takes place, decision with the highest rating go on to next steps.

7. **Decision Documentation**, architect and other company participants document the set of decisions that received higher ratings. The documentation describes the architectural solution and the forces in favour of the decision and the forces against the decision.

8. **Decision Evaluation**, the decisions are evaluated, all participants vote whether the decision is good, acceptable or has to be reconsidered.

9. **Retrospectives and Reporting**, the review team collects artifacts to come up with a report in future.

4 Extreme Programming and Architectural Relation

Lindstrom et al. [11] describes Extreme Programming as "A discipline of software development based on values of simplicity, communication, feedback, and courage." Whole team, is used for describing the participants of XP. The team consists of business/development/testing team and customer who works with them in daily basis. The core XP practises are Whole Team, Planning Game, Small Releases, and Acceptance Test. Extreme Programmers work together in pairs or in groups and use practises called Pair Programming, Simple Design, Test-Driven Development, and Design Improvement. A visualisation of each iteration and the relationships between the customer and the developers can be seen in figure 2.

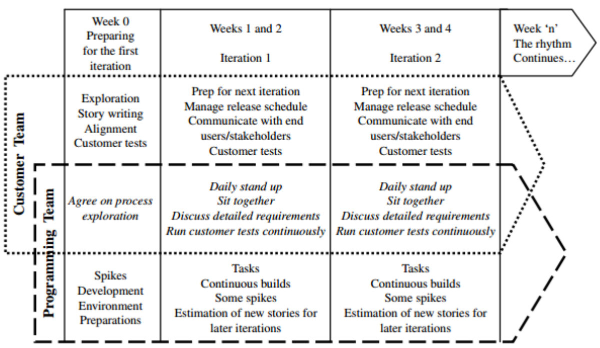

Fig. 2: Visualisation of XP iterations. [11]

Even though XP does not explicitly require a concept architecture in it's methodology, as mentioned in Section 1, all of the systems with a reliable size and interrelations between components have an architecture. XP has 12 core practises and among them 2 gives bits of information that can guide to this implicit architecture. These practises can be listed as;

1. **Planning Game**: This practice includes Release planning and Iteration planning. Release planning is where the customer presents the desired features and the programmers estimate their difficulty. With the difficulties taken in mind the Customer lays out a plan. Iteration planning is a plan for each iteration which can be seen in figure 2. XP teams build software in two weeks, in each iteration, which is runnable. The planning game includes user stories, which are much like use cases however they are different because they are not as detailed as use cases nor they require heavy-documentation. By putting each piece of user stories together, one can achieve a general overview of the system's architecture.

2. **Metaphor**: Metaphor is the simple description of how the program works, with, if possible, real metaphors. This is to be sure that everybody understand what the program does. While defining and describing a system, involuntarily architecture of the system will also be partially defined. By combining these partial definitions an overall software architecture of the system can be defined.

Architectural spikes are also a concept that is been introduced in XP. Spikes solutions are programs aimed to solve a specific problem. Architectural spikes are aimed at solving architectural problems in the iteration 0. It can be argued that architectural spikes can define a software architecture for the system when combined. However El-Khawaga et al.[7] defines this as "combination of spikes to come up with an architecture is like thinking that a vertical slice of a not-uniformed soil can be used as a determinant of characteristics of a vast desert.".

As one can see even though XP's arguable offerings for implicit architecture formed by several concepts and practices exist, it does not offer a way to evaluate the software architecture of the system at all. For this issue, we have reviewed some of the embeddings of software architecture evaluation methods into XP taken from primary studies.

5 Embeddings of Software Architecture Evaluation Methods in XP

5.1 CAR[1] and RAQ[2] methods:

Sharifloo et al [16], introduce the CAR and RAQ methods and they are defined and used in the following way:

1. **CAR** - In continuous architectural re factoring, smells in the architecture are discovered and solutions to revise them would be identified. Architectural smells according to Martin Lippert and Stephen Rock [12] are some patterns that affect system from different aspects(Architectural qualities/ quality attributes). This method is developed in order to work in parallel with XP[3] so as to keep the agility of XP intact.
   To make CAR possible, the authors defined a role called Architect where by the architect will continuously receive partial models from the development team, and be responsible for coming up with solutions to remove architectural smells. The new models are then integrated with the older ones to make a partial architectural diagram. When model integration occurs, the architect will do an analysis on the complete architectural diagram to identify smells and provide solutions for them as new tasks. Although CAR can analyze some of the quality attributes such as modifiability, extendability and scalability that are important to developers, according to the authors, CAR is still not enough because (1) it is done only by the architect, not taking others' opinion into account and (2) not all quality attributes could be analyzed efficiently in the CAR practice like performance. And, this is why the provide a second complimentary method RAQ to cover the problems of CAR.

2. **RAQ** - This method occurs at the end of all the iterations according to the authors and, it's main goal is to test the working system that outcomes a iteration according to customer requirements. They go further to explain the steps to performing this method, which include:

   (a) Preparing the structure of the session and identifying representatives of stakeholders to join the session.

[1]Continuous Architectural Refactoring
[2]Real Architecture Qualification
[3]Extreme Programming

(b) Describing, in brief, final architectural model of the iteration that is integrated using partial models.

(c) Describing, in brief, refactoring decisions that have be made by architect and ask members to express their opinions about them.

(d) Identifying architectural aspects (quality attributes) that should be analyzed in the session.

(e) For each quality attribute specified in step 4:

i. Start a brainstorming sub-session, taking stakeholder‘s opinions into account about their experience when working with current working system.

ii. Decide about solutions for new needs and requests that current working system cannot provide or han dle.

iii. Defining new solutions as concrete new tasks and tak ing them as unfinished tasks.

5.2 Architecture-centric approach (QAW[4], ADD[5] an ATAM/ CBAM) and XP

Briefly, an architecture-centric approach in XP as described by Rober L. Nord et al [15] would work in the following way. QAWs provid a method for analysing a systems architecture against a number o critical quality attributes, such as availability, performance, security interoperability, and modifiability, that are derived from mission o business goals[4]. In XP, system analysts elicit, capture, document, and analyse requirements. Since QAW is held early on in the development process, and focuses on the stakeholders, this can be embedded into XP in the first iteration during the story production therefore helping to show quality attributes in terms of scenarios. These scenarios help to supplement the user stories. Finally, the presence of an on-site customer that XP prescribes, which is sometimes criticised is complimented by the gathering of stakeholders in QAW.

ADD, a systematic step by step method of designing the software architecture of a software intensive system can be embedded into XP at the design stage. Since both breadth first and depth first decomposition approaches are supported by ADD, it therefore supports and XP approach by allowing an initial breadth-first decomposition for the first decomposition level, followed by depth-first decompositions to explore the risks associated with change through prototyping. Even though it differs from XP in a way that it emphasises addressing quality attribute requirements explicitly, the planning would help the developers better understand the impact of changes to requirements.

ATAM and CBAM as described in Chapter 3.1 and 3.2 are evaluation methods, and these can be embedded into XP at the testing and analysis stage.The ATAM and CBAM methods can be done right after the ADD method to track technical and business risks early in the process and to help prioritise stories for the next release. Evaluation of the design can occur by the use of the scenarios collected by performing QAWs, which will provide input for analysis during testing. So, ATAM provides architects with a framework for understanding technical trade-offs and risks they face as they make design decisions, and CBAM furthermore helps the architects consider the return on investment of architectural decisions.

6 Embedding DCAR into XP

In the embeddings that we have discussed, both of the SAEMs are scenario-based. As mentioned in van Heesch et al. study[17], an architectural evaluation method for agile methods should be light-weight and should not consume a lot of time and resources. DCAR is a lightweight evaluation system, where a session takes a half-day, requiring presence of three to five members of the project team including an architect role. Scenario-based evaluation methods try to ensure that a whole system satisfies its quality requirements while DCAR can concentrate on a set of architectural decisions. These two properties of DCAR is the reason why we offer embedding DCAR into XP.

For DCAR to work with XP, a lead architect, could be anyone within the team or could be outsources, should be defined. Lead architect should have prior software architecture knowledge and should have a good understanding of the domain of the project that is being developed. This is an addition to XP since XP does not include any additional roles other than Customer and Developer Team.

A DCAR session should take place in the iteration 0 described in figure 2. Iteration 0 includes development of architectural spikes and forming of user stories. Iteration 0 consists of Exploration Phase and Planning Phase which are illustrated in figure 3.

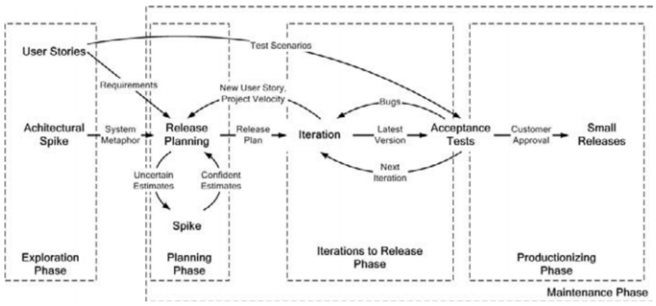

Fig. 3: Life Cycle of an XP project. [2]

With given user stories, architectural spikes and system metaphor, the lead architect should come up with a presentation that should contain the most important architectural requirements, high-level views of the architecture, the approaches used (such as patterns or styles), and the technologies used. Rest of the steps of a DCAR session, described in section 3.3, will take place and the evaluation reports will be handed in to the development team before the start of iteration 1. This may look as if a Big Design Up Front will be emerging, which would be against XP's values. However, this issue will resolve in the DCAR session that will take in the upcoming iterations where the architecture of the system will gradually evolve. In every iteration the development team will form a short report including a brief descriptive model of the features that they have developed. Same behaviour can be seen in the embedding that was mentioned in section 5.1. At the end of the iteration, the architect would have enough models to enhance the decided architecture in the DCAR session in iteration 0. At the end of the iteration, a DCAR session takes place and evaluation reports are handed out to the development team before the next iteration. An illustration of how DCAR sessions are embedded in between each iteration of the XP in figure 4.

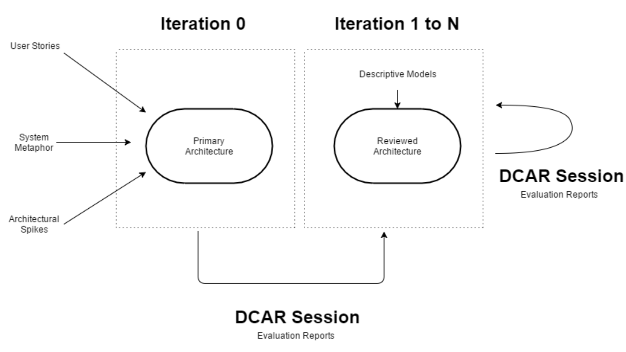

Fig. 4: Embedding of DCAR in XP.

[4] Quality Attribute Workshop
[5] Attribute driven design

Criterion	**Architecture-centric approach and XP**	**CAR and RAQ**	**DCAR**
Individual and Interaction	In the architecture-centric approach, the interaction involved includes the stakeholders, system analysts, the on-site customer, and architect. Although documentation is needed, XP tries to reduce on it and encourage conversation.	In CAR, in the context of XP, individuals work by themselves when they are coming up with the descriptive models, in the case of pair-programming they will also interact with each other while forming the descriptive models. Also RAQ requires interaction between the participants.	In DCAR, architect, the developers, customer and management all work independently until their presentations. Interaction between the participants are critical in all steps of the DCAR, especially in the Forces and Decision Completion. All of the decisions are taken in a collaborative manner.
Documentation	There is a significant reduction in terms of documentation in the architecture methods used here due to the XP method but even then, documentation is still required and important for this approach.	CAR and RAQ only need structural models to understand the probable smells. It also needs brief descriptive models from developers.	DCAR embedded in XP, requires brief descriptive modeling in each iteration. DCAR itself does not require any additional documents apart from the intermediates that it creates in the sessions and the decision evaluation report.
Customer Collaboration	The customer is involved in two architecture steps in this approach that is QAW ATAM/CBAM and included in the XP aspects.	Customer role is defined in XP, additionally customer joins RAQ.	Customer takes part in daily meetings in XP. DCAR, in most of it's steps include the customer when making architectural decisions and reviewing them.
Responding to changes	There is no immediate architectural analysis done of changes made in the architecture.	CAR, by architectural refactoring ensures that the architecture adapts to changes.	DCAR embedded in XP, ensures that changes in the user stories and descriptive models are reflected on the architecture. Also, decision forces are mutable and they respond to changes in the companies goals, business goals, emergence of new technologies. As DCAR uses these forces to make architectural decision, DCAR is considered a highly reactive method.
Simplicity	For the application of the architecture methods in this approach, a high level of skill and experience is required and in addition to that,collaboration with stakeholders is hard for the XP team.	An addition of architect is defined in CAR, but basic skills are enough for this role. CAR is concurrently works within the lifecycle of XP.	The light-weight nature of DCAR embedded in XP creates a simple method to evaluate the software architecture of the system.
Feedback	During the architecture methods, lots of feedback is gathered from stakeholders.	Developers get feedback from architect through CAR. RAQ also gives feedback to all of the participants.	Feedback is given to the developers after each DCAR session. Within the DCAR session, due to it's collaborative nature, feedback between the participants are mostly seen.
Time Overhead	Project time may be increased unpredictably since the methods involved in this approach require a lot of time.	CAR is concurrent to the development and does not require any additional time. RAQ requires estimable time.	A session takes a half-day for DCAR.
Cost Overhead	Possible increased costs due to the need to hire skilled staff who can perform the architectural methods in this approach.	An addition of architect is required in CAR and RAQ.	DCAR does require an architect which could be anyone in the team with knowledge of software architecture. No additional costs are required for this method.
Quality Improvement	The quality of the final product will be increased due to the three different architectural methods, each complimenting XP with their advantages	Quality attributes are satisfied with both CAR and RAQ	Quality of the system increases swiftly as each of the architectural decisions are reviewed and applied in the development. Since DCAR favours involvement of many stakeholders, the architectural decisions are reviewed from many perspectives and quality of the decisions are ensured.

Table 2: Comparison of Embeddings

DCAR, is well suited for architectural evaluation in XP since, collaboration between the customers and the developers are intuitive both in DCAR and XP. Communication, is a value of XP and DCAR within it's sessions supports communication between all of the participants. Simplicity, is also a value of XP. DCAR, with it's light-weight methodology, satisfies this value. Feedback value of XP is satisfied with decision evaluation reports from each session of DCAR.

7 Comparison of the Embedding Strategies

Table 2 shows multiple comparisons between the embedding talked about in 5.2, 5.1 and our own approach of embedding DCAR into XP. As mentioned in methodology, the criterion are derived from agile manifesto and from Sharifloo et al. [16].

8 Conclusion and Future Research Directions

In our research we have described certain SAEMs and how they were embedded into the agile method Extreme Programming. We have seen that certain SAEMs changed their stucture in order to fit into XP. We have also introduced a new strategy to combine XP with DCAR. By looking at the comparison, it is possible to say that CAR RAQ and our approach of embedding is more suitable for XP since they match with the values of XP. There is no evident winner between our approach and CAR RAQ either. For further research on this topic, surveys could be given to the companies that uses these embeddings in their project and collected information could be used to compare these embeddings. Our own approach of embedding DCAR into XP is theoretical in the sense that we did not have the time nor the resource to see our method of embedding in industry. For further study, our method of embedding can be used in several projects and surveys could be collected asking if the method is successful or not.

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A Comparison of Context-Aware Power Management Systems

J.T. Brandsma and Y.W. Tijsma

Abstract—The energy consumption of Information and Communication Technology (ICT) has shown an increasing trend over the last few years. Especially user devices in office environments and homes are responsible for a large part of this growth. Research shows that energy consumption management by users is far from optimal. Due to this many automated power management systems have been developed. In this paper several different systems for saving energy in large computing environments will be studied. We will focus on PoliSave, E-Net-Manager, Gicomp and Green Office. These systems will be compared based on complexity, user interfaces, needed resources and of course the total reduction of energy consumption. In conclusion the three different systems do not differ much in intrusiveness and user interface, however there is a difference in the energy consumption and the costs. Overall E-Net-Manager is the most sophisticated system with the best energy saving potential.

Index Terms—Power management, large computing environments, sensors, intrusiveness, energy waste, green computing

1 Introduction

Due to the advancements in the Information and Communication Technology (ICT) the use of computer facilities have increased substantially and have become an important tool in our society. As a result, the last few years have shown a huge increase of power consumption of ICT facilities. According to [5], the ICT sector was responsible for 3.7% of the total global energy consumption in 2007. The relative share of the ICT facilities increased to 4.6% in 2012. Other research [6] also shows this trend of increased power consumption and concludes that this trend will continue to hold in the future. A large portion of this consumption can be ascribed to user devices such as Personal Computers (PC) and displays. A regular display will consume 29.60 Watt and a regular PC will consume 98.86 Watt. This adds up to 128.46 Watt [9]. Even though a single device does not consume a lot of energy, the sheer number of devices used nowadays combined with their utilization time makes the total consumed energy relevant.

Recent studies [4] show that a significant part of consumed energy is wasted due to inefficient use of previously mentioned user devices. For example people tend to not turn their display off when it is not being used actively. T. Brady *et al.* [2] discovered that 60% of all PCs in an office environment were never turned off. Furthermore only 6% of all PCs use the sleep state technologies which are available for the PCs. If the PCs do make use of such technologies, the power consumption could be reduced by 95% or more [3]. This translates to a reduction of costs between $10.97 and $95 per computer per year [14].

The increase of power consumption coupled with an increasing environmental awareness of the general public has led to energy consumption being a key challenge in the ICT sector. This field of research is known as ‘Green Computing’. ‘Green Computing’ is defined as the effective and efficient use of computers and related technology by humans in an eco-friendly manner which minimizes the impact of carbon emissions on our environment [13]. Researchers in this field are putting effort in several areas to achieve energy reduction: energy consumption, E-waste recycling, data center consolidation and optimization, virtualization, and IT products and e-labeling [14].

In this paper we will focus on the area of energy consumption. Several systems have been developed in order to counter the energy waste due to computer usage. These systems make use of different techniques and sensors to achieve a reduction of wasted energy with varied results.

Our research will focus on the comparison of PoliSave [4]: a power management system for PCs developed at the University of Turin, E-Net-Manager [3]: a power management system for networked based on soft sensors developed at University of Pisa, and Gicomp [7]: a monitoring and management platform for IT and home appliances developed at the University of Poznań. These systems will be compared based on the user interface, intrusiveness for the user, results on energy savings, complexity, and costs. These systems are deployed in environments such as office spaces and homes. We consider these systems from a viewpoint of a user who does not want to experience negative consequences using these systems. Furthermore, we look at the systems from a management perspective as they want to achieve a reduction of wasted energy and costs.

This paper is organized as follows: section 2 provides an overview of the functionality, architecture and results of the systems that we will compare. In section 3 the comparison of the systems is described. Section 4 contains a discussion of the results. Finally, conclusions are drawn in section 5 and future work is discussed in section 6.

2 Description of Methods

In this section we will give an overview of the details of the three systems. The systems will be described by their architecture, user interface and results of saving energy. Also some system specific characteristics are mentioned. Based on these metrics, results to answer the initial research question can be derived.

2.1 PoliSave

PoliSave was developed to monitor the power consumption of networked devices focusing mainly on PC usage. PoliSave offers a centralized web-based architecture which allows users to automatically schedule the power state of their PCs. The developers of PoliSave defined a number of requirements that PoliSave should take into account. It should address the following requirements: 1) heterogeneity, both in terms of users and operating systems; 2) remote control, the power management actions need to be performed remotely; 3) simple GUI, the complexity of the control panel offered by OSes was identified as one of the major problems; 4) custom deployment, the software can be either installed manually or automatically installed; 5) security, this has to be guaranteed since actions are performed remotely; 6) consistent information, the software has to handle association between a PC and its user.

Given the previously presented requirements an architecture was developed consisting of three main components: a server, a client and a communication protocol. The client manages the actual powering off mechanism. During this study, two client architectures were developed: one architecture for Windows and one architecture for Linux. Both architectures have one component that communicates with the server and a second component that displays pop-up messages to communicate with the user. These pop-ups are used to warn a user of an action that is going to happen and allows the user to override these actions. The actions are performed by invoking the primitives of the Hardware Abstraction Layer (HAL). HAL allows you to control the

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power state of the PC. The core part of the architecture of PoliSave is the server which performs client remote power control. Also, it manages the database of clients. This includes the scheduled events of users. Using a web interface the users can access the operations that are managed by the server. Users are free to specify a timetable that stores scheduled actions like stand-by, hibernation, power-off and power-on. The server is able to automatically perform these operations. On top of this the user can perform real time actions such as turning on the PC themselves. Finally, there are the communication protocols that make sure the actions can be executed. All protocol messages are encrypted using the HTTP protocol and OpenSSl libraries to guarantee privacy.

The system was installed on 70 PCs of users of the Electrical Engineering Department (EEDept). The time was in slots of 15 minutes. The function $I_x(i)$ is applicable for every device x:

$$I_x(i) = \begin{cases} 0, & \text{if } x \text{ is OFF} \\ 1, & \text{if } x \text{ is ON} \end{cases} \tag{1}$$

Then, the total amount of times x is on in a given day D is computed by:

$$ON_x(D) = 15m \sum_{i \in D} I_x(i) \tag{2}$$

Finally, the average over the set K of days in the data set is calculated, obtaining the average time of the device x is active per day, i.e.: the host daily average up-time:

$$ON_x = \frac{\sum_{D \in K} ON_x(D)}{|K|} \tag{3}$$

Figure 1 visualises the results of the testing. Figure 1(left) shows the comparison between two cumulative distribution function (CDF). The CDFs show $ON_x(K)$ for $x \in \{PoliSave\}$ and $ON_x(K)$ for $x \notin \{PoliSave\} \cap \{EEDept\}$; $K = \{Mon, Tue, Wed, Thu, Fri\}$. Figure 1(right) depicts the number of ON and OFF events recorded during one week. Most of the PCs running PoliSave are turned on in the morning and turned off during the late evening. Based on Figure 1 the developers concluded that normally about 53% of PCs without PoliSave are always turned on, but with PoliSave this percentage drops to less than 6%. On top of this most PCs are on for less than 12 hours a day. PoliSave reduces the average up-time of PCs from 15.9 hours a day to 9.7 hours a day. So PoliSave saves on average more than 6 hours per working day. This translates to an annual saving of about 0.6 kW/h per PC per day. Using PoliSave the University of Turin managed to save more than 250,000 Euros per year.

In order to further improve the effectiveness of PoliSave the developers plan to customize the monitor capability, so that individual users can track the power consumption of their PCs. Another improvement is to introduce active learning techniques to track the user activity and then compute the best power scheme to apply for each user.

2.2 E-Net-Manager

Scientists of the university of Pisa decided a power management system was needed to reduce the waste of energy due to user behaviour. Figure 2 shows the results of monitoring the energy consumption of the university campus for 2 months. This gave the scientists not only insight in the energy consumption, but also in the behaviour of users regarding energy consumption. Figure 2 shows that many devices are never turned off even during nights or holidays. To reduce this unnecessary waste of energy, E-Net-Manager was proposed.

E-Net-Manager is an automated context-aware power management system. It is based on different sensors and software tools already

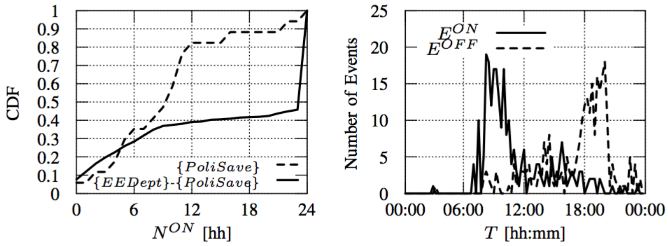

Fig. 1. (left) Host daily average up-time for PCs in the trial and for other PCs. (right) Number of on and off events recorded every 15 minutes from [4]

available in the environment to capture information about the user and the environment. These sensors are also known as soft sensors. Some of these soft sensors could be: attendance recorders, Bluetooth-enabled mobile phones and software tools such as Google Calendar and PC activity monitors. E-Net-Manager tries to be as flexible as possible to support different users and environments. By using soft sensors instead of sensors that need to be bought specifically for this purpose, the costs of E-Net-Manager will be relatively low.

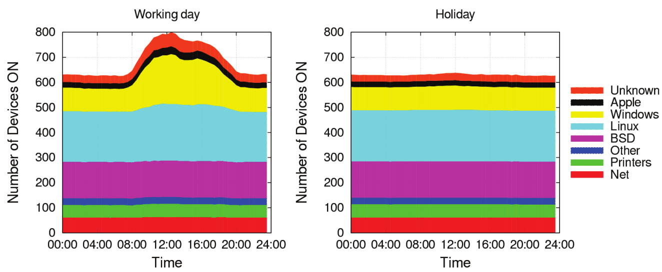

Fig. 2. Number of active devices during the day from [3]

In order to have a user friendly system, it has to have a set of features that support the needs of the users and management. The main feature of E-Net-Manager is to determine whether PCs are used, so they can be turned off when not in use. To derive the correct information that is needed, E-Net-Manager obtains data from both the user and the soft sensors. Besides this main feature, E-Net-Manager provides some other features. One of these supporting functionalities is Static Control. This functionality allows the user to specify rules for their PC to be turned on or off at specific times. A user can simply add a rule to turn the PC off outside office hours. In some cases this will result in saving energy for approximately 16 hours per day. Another supporting feature is called Presence Detection. Presence detection is the process of determining based on soft sensors whether a user is or is not in the office. When the user is not in the proximity of his or her PC, a command will be send to suspend or power off the machine. The last functional feature is named Remote Control. This feature gives users the possibility to remotely control their PC.

Besides the functional features, E-Net-Manager was developed with some important non-functional requirements in mind. Presence of a user is considered highly sensitive data. To protect this, the system needed to be secure and ensure privacy of its users. Other important factors are low intrusiveness for the users and high interoperability to work with any PC, independently of its operating system.

The architecture of E-Net-Manager consists of several components. As can be seen in Figure 4 the architecture follows the client-server paradigm. All components shown in this figure communicate with the *eXtensible Messaging and Presence Protocol* (XMPP) [12]. This protocol supports SSL and TLS encryption to create confidentiality and server authentication.

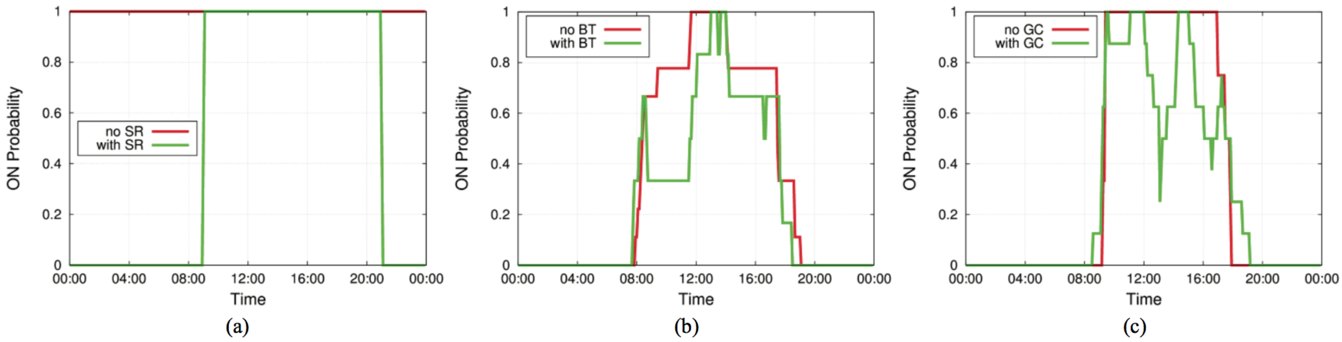

Fig. 3. PC activity in a working day with and without the usage of Static Rules (a), Bluetooth soft sensor (b) and Google Calendar soft sensor (c) from [3]

The server consists of four different types of servers. It contains a database server, a web server, an XMPP server and a manager server. The database stores the information about PCs, soft sensors and the static rules defined by users. The web server serves the web interface of E-Net-Manager to all users. The interface allows users to check the state of their PC, control their PC remotely, define rules for their machine and view the current settings of their soft sensors. For communication between all the components, the XMPP server is set up. The power manager takes care of organizing the static rules defined by users. When it determines a PC needs to be shut down or suspended, it will send a message to the corresponding machine. When a PC needs to be woken up, a message will be send to the waker component. For waking up PCs, E-Net-Manager relies on Wake-on-LAN [15].

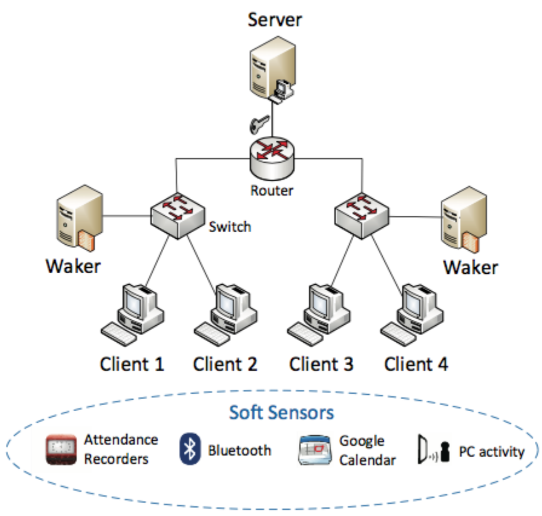

Fig. 4. Architecture of the E-Net-Manager from [3]

E-Net-Manager was tested in a real environment on the campus of the university of Pisa. It considered 20 PCs with different operating systems. The activity of users was measured over a period of two weeks to determine the normal behaviour. At the end of this period E-Net-Manager was enabled and tested for another two weeks. Results of this test show that users who did not care about their energy consumption at all, achieved great results with simply setting some rules, they saved up to 50%. This can be seen in Figure 3 (a). Users who already paid more attention to their consumption also improved due to the soft sensors. Figure 3 (b) and (c) show two different users using Bluetooth and Google Calendar. Energy consumption of PCs have been reduced by 9.4% and 10.3% due to Bluetooth and Google Calendar. These results show clearly that E-Net-Manager can significantly reduce the energy consumption of large computing environments.

2.3 Gicomp

Researchers of the university of Poznań in Poland developed Gicomp with the main purpose to create a power management tool that combines various related tools and solutions. Gicomp is built on the work of [10] which introduces the SMOA Devices platform. This platform is a project that measures energy consumption with homebrew measuring devices. These devices consists of a small watt meter and a Zigbee [1] component for wireless communication. To support multiple environments, Gicomp can be deployed in offices, but also in homes. Besides this, the developers created it to be extensible and standards-based. This means third parties can easily contribute to the project by implementing extra features.

The architecture of Gicomp, as can be seen in Figure 5, is designed to be easily set up. All devices in the network are set up to act as a node. These nodes have their own identifier in an XMPP network. Every node can have one of three different roles: Device node, Waker node or Meter node. The device node communicates with the operating system to use the power management features already available. Waker nodes are responsible for waking up machines when they are shut down. For this the Wake-on-LAN protocol is used. Meter nodes act as an interface between the actual meters and the service that has control over everything. The service is the central point of Gicomp which unites the information of all nodes.

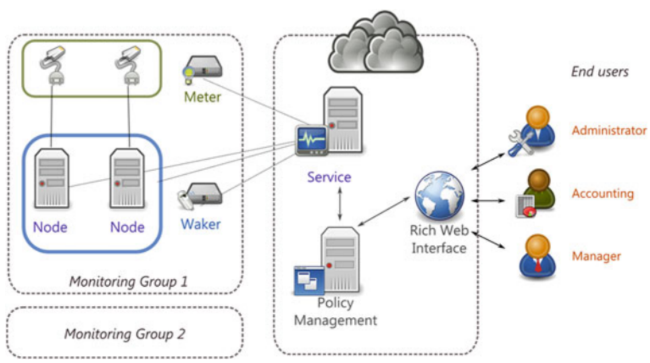

Fig. 5. Architecture of Gicomp from [7]

Based on this information, a web dashboard is created to give feedback to the users and the management. By showing this information, users will learn more on their energy consumption. This could encourage them to pay attention to their energy saving behaviour. Also management can access the relevant data. Sharing this information gives insights in energy consumption of whole divisions or even entire

	User perspective		Management perspective		
	Intrusiveness	User interface	Energy savings	Complexity	Costs
PoliSave	⋆⋆⋆	⋆⋆⋆	⋆⋆⋆⋆	⋆⋆⋆⋆	⋆⋆⋆⋆
E-Net-Manager	⋆⋆⋆⋆	⋆⋆⋆⋆⋆	⋆⋆⋆⋆⋆	⋆⋆⋆	⋆⋆⋆
Gicomp	⋆⋆⋆⋆⋆	⋆⋆⋆⋆⋆	⋆⋆	⋆⋆⋆⋆	⋆⋆

Table 1. Comparison between PoliSave, E-Net-Manager and Gicomp. More stars mean a better score for this metric.

buildings. The web dashboard is also available for home owners. This could help people save energy to get a lower energy bill.

Results of Gicomp depends mainly on the behaviour of users itself. If users decide to actively (remotely) shutdown their devices, energy consumption will decrease. The main advantage of Gicomp is giving users insights in their energy consumption. In the ideal situation this will alter the behaviour of users to be more active in energy savings. In office environments Gicomp can be used by building managers to shutdown machines remotely outside working hours.

3 Results

This section lists the results of comparing Gicomp, E-Net-Manager and PoliSave. In the user perspective section we will look at the metrics that are relevant for the users. In the management perspective section we will look into the metrics that are more relevant to management. Table 1 gives an overview of the compared metrics.

3.1 User Perspective

We can categorize these three systems based on three different levels of intrusiveness. First we have Gicomp that does not interact with the user in any way. Both E-Net-Manager and PoliSave require more interaction with the user as both systems work with timetables that the users have to specify themselves. Since E-Net-Manager is able to gather additional information and combine this with the specified timetables, it can more accurately predict when a PC can be turned off. PoliSave on the other hand has no such functionality and relies on pop-ups to gather feedback from the user if the PC should be turned off based on the predefined timetable. Therefore we conclude that PoliSave is slightly more intrusive compared to E-Net-Manager and Gicomp is the least intrusive.

The second metric used to judge the systems is the quality of the user interface. In order to give both user and management parties insight in the energy consumption, a clear user interface is necessary. Gicomp delivers an extended user interface to view the energy consumption. The interface of Gicomp also allows building managers to create groups. These groups can than be controlled at once. The same functionalities are available in the user interface of E-Net-Manager. PoliSave's user interface is a bit less sophisticated. It only allows the user to add or modify the timetables of their PCs.

3.2 Management Perspective

One of the most important aspects for any management group is the finanicial aspect. In order to adopt a system, the energy savings results have to be indisputable. Unfortunately Gicomp is never tested in a real environment. Therefore no well founded conclusions can be drawn for this system. However, based on the functionalities of Gicomp we can make an educated guess. Since the only energy saving functionality of Gicomp is remotely suspending or shutting down machines, we can assume the energy savings will never be better than PoliSave or E-Net-Manager. We think it is safe to assume that Gicomp will only save energy outside office hours. E-Net-Manager is a more sophisticated system with more intelligent energy saving methods. As mentioned in section 2.2 the results of E-Net-Manager show that on average it can save at least 9.4% on every PC, even when users are already more involved in energy savings. The results for PoliSave show the same trend as the results of E-Net-Manager. On average a PC that is connected to PoliSave is 6 hours per working day less on.

Another important factor in adopting a system is the complexity. A very efficient system can be hard to maintain and therefor not desirable. By looking at the architecture of the different systems we derived the complexity of initializing and maintaining the different set ups. Gicomp is relatively easy to set up and maintain. A small piece of software needs to be installed on every PC in the network. After this all devices simply connect to one main server. This means there is no complicated server setup necessary. On the other hand, E-Net-Manager requires four different types of servers that all have to work together. This communication is simplified by using a standard communication protocol, however the hardware configuration could be more complicated. Besides this, every sub network in the actual network needs another waker module to be able to work. PoliSave is easier to initially set up. This is due to the fact that it only requires one central server, just like Gicomp. It also needs to install a small program on every PC, just like the others.

In order to have a system that will not take too long to be at least break-even in terms of money, the initial costs cannot be too high. That is why we also took a look at the costs of the hardware. Gicomp can become very expensive due to the required sensors. Depending on how much data is required, a relatively high number of sensors is necessary to give a good overview of the energy consumption. E-Net-Manager and PoliSave only need sensors that are already available in the environment. This means no extra is money is needed for an initial setup. However, E-Net-Manager requires four different types of servers. When an organization is interested in E-Net-Manager it will have to take these costs into consideration. For the other two systems only one server is required.

4 Discussion

We can divide the three systems into two different categories: an active energy power management system and a passive power management system. E-Net-Manager and PoliSave fall into the first category because both systems turn PCs on/off automatically based on the available information. Gicomp can be placed into the last category, because this system is able to turn PCs on/off remotely, but only by hand.

When comparing these systems to see which is the best option, we think that it is not a good option to look at the aspects of the systems individually as some aspects are trade offs. For example, costs and intrusiveness are a trade off. If the user wants to experience low intrusiveness of the system, the costs of the system will rise. The costs could be higher due to the usage of more sensors to detect user activity.

Another thing to note is that we can not properly compare the efficiency of the systems. The result of PoliSave is a reduction of 0.6kW/h per PC per day. E-Net-Manager reduces the energy consumption by at least 9.4% and Gicomp was never properly tested. Therefore we are unable to compare the effectiveness of the systems based on raw numbers. Although the effectiveness of PoliSave and E-Net-Manager are both quantified, we can not really compare the two as different metrics were used to measure the energy reduction.

Finally, it is worth mentioning that all systems were developed in recent years. However we noticed that E-Net-Manager and Gicomp are more advanced compared to PoliSave as they rely less on user input and more on information provided by sensors. We assume that this is caused by the fact that PoliSave was developed in 2010 whereas Gicomp was developed in 2013 and E-Net-Manager in 2014. The developers of Gicomp and E-Net-Manager had access to more results of previous projects.

In order to find more statistically founded results, an experiment should be conducted in a similar environment. In this way the systems could be judged on the same set of metrics. Such an experiment would result in more cohesive results that can be reliably compared.

Although these systems are able to reduce the energy consumption, we think that the results can still be improved. PoliSave and E-Net-Manager both use rules specified by the user to save energy. This is not very flexible in our opinion. A user might deviate from this schedule or completely change it. In the case of PoliSave the user has to cancel the suspend action. E-Net-Manager handles this better by using additional information from sensors. We think it is a good idea to use machine learning to improve the adaptability of the system. Using this technique the system should be able to deduce the rules for each user and change them accordingly when needed. This will also reduce the intrusiveness of such a system, because the user does not have to specify the rules anymore.

Finally, we would like to mention that, although these systems achieve energy reduction, there are more areas where reduction of energy consumption could be achieved. A context-aware power management system alone will have limited results, but if more energy saving techniques are used these results can be improved even further.

5 Conclusion

This paper has shown that context-aware power management systems can significantly reduce the energy consumption of a large computing environment saving thousands of Euros. However we can not say when such an investment will result in a profit as none of the papers provided any information about the costs of the system. We can only make a relative comparison between the systems. When we order the systems by costs, we think that PoliSave is the cheapest system as it uses only a server as additional hardware. E-Net-Manager is slightly more expensive, because it uses multiple servers and sensors. Gicomp will be the most expensive option, because it uses the most amount of sensors of all the three systems.

We discussed several context-aware power management systems with their advantages and disadvantages. We think that the most sophisticated system, E-Net-Manager, proves itself to be the best option out of three, because the user hardly experiences any negative consequences and it has a relative low costs. Furthermore it achieves a significant reduction in terms of energy usages.

6 Future work

Finally, we would like to provide our vision of the future in this field. More research will be conducted in the near future to improve the current context-aware power management systems and discover new techniques to reduce energy consumption. L. Chiaraviglio, the developer of Polisave, and R.M. Llamas *et al.* [11] indicate that generating rules automatically using machine learning will become more popular.

M. Kazandjieva *et al.* [8] state that context-aware power management systems could be introduced for a single PC. The aim of such a system would be to gather information about the best place for the execution of an application. This could be either in the cloud or locally on a PC.

Lastly, we think a context-aware power management system should be developed for cloud computing systems. Such a system would monitor the usage of the clusters and then turn them off when they are not used and turn them on when more computation power is needed.

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Information and Communication Technology for Smart Grids: Current State and Trend

Antonios Koutounidis and Maarten Kollenstart

Abstract—Because renewable energy sources are not constant, the power grid must transform into a smart grid. In a smart grid, the energy can be monitored more efficiently. We selected and discussed some of the challenges and possible implementations and we try to identify which new techniques for the power grid are able to counteract the effect of the challenges. Focusing on information and communication technology techniques rather than the physical techniques. One way of doing so is by implementing microgrids that are able to communicate with each other, for this a Multi-Agent System fashion implementation can be used. Since the network is huge, we expect enormous amount of data to be generated, therefore, we represent advanced techniques to manage this data.

Index Terms—Power grid, smart grid, power system distribution, demand response, multi-agent system, microgrid, dynamic grid, smart metering, data management.

1 Introduction

The power grid (PG) is a gigantic complex by which electrical power is distributed from suppliers to consumers. Traditionally, the PG's purpose is to transmit electricity from few central power generators, in which they generally use fossil fuels, to an enormous amount of users. This is an aged system architecture which is not reliable, not environmental friendly, and is not covering the needs of our society anymore. In order to retain our climate and environment viable while at the same time reduce the waste of energy and increase the reliability of our power networks, we need to implement a more sufficient system.

This system is called smart grid (SG) and has already been introduced in the past few years. SG uses, in addition to an electricity flow, an information flow, with the purpose of creating an automated and distributed advanced energy network. This can be achieved by adopting modern information technologies, so SG is able to transmit power in more efficient ways by using advance data that is collected from smart meters around the network. With data analysis techniques and computational intelligence algorithms the network is able to understand the behavior of the connected users and adopt the specific strategies to satisfy sufficiently the needs of the users.

Data gathering and statistical algorithms are used already by energy companies to predict the usage of electricity. This data gathering is currently done by sensors in while distributing the energy and not at the consumption side. By providing customers with relative quite straightforward smart meters that collect consumption information they share with the energy company and with users, energy companies do move to more consumption based statistics.[10]

Another aspect of the SG is the electronic and material engineering. New electronic technologies and materials are being discovered as technology is developed. In addition the aged network infrastructure is not reliable and efficient anymore. For these reasons the infrastructures of the complex network must be renovated and in some situations completely be changed in order to maintain a reliable, sufficient, and environmentally sustainable system.

Although the main concepts and ideas behind the SG are the same, different political regions around the world have their own perspective about the implementation and the goals of a SG. In the United States their main goal is to change the network from a centralized to one that is less centralized and gives the opportunity to the consumers to be more interactive [23]. In China SG refers to a more physical network approach to ensure security, reliability, and environmental sustainability [25]. On the other hand in Europe SG refers to a broader society participation and integration of all European countries in an RE-based system [5].

In this paper we adopt at most the US point of view. We mention the current state of the PGs, the reasons we need to proceed to a SG, and how we can implement that. We mainly focus on the information and communication technology aspects of the smart grid, rather than the physical aspects of the network.

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2 Current state/Challenges

The foundations of the current PG have been laid in the 1960s. The idea behind the PG at that time was of course different than the way we think now of our power consumption and power generation. In its current state the PG assumes there are several power generators with a high power generation and a high number of energy consumers. This leads to an extensive distribution network that distributes the energy from the power plants to the power consumers. A simplified idea of the traditional PG is shown in figure 1. Where the PG is illustrated in a pipeline manner, from generation to transmission then on to the distribution lines and ending at the users of the electricity.

Most of the electricity is generated by using fossil-fuels, in the United States the fossil-fuels took up to 67.2% of the electricity production in 2015[22]. Supporting the current infrastructure of the PG, as these fossil-fuel plants produce electricity for a large number of consumers. Noting that the 67.2% of the electricity production only contains the fossil-fuels and nuclear electric power is counted as separate category, the amount of large scale power production plants is the vast majority of electricity production.

As the distance between the generation of electricity and the consumption of electricity is often very large, due to the fact that there are only a few electricity generators, the length of path the electricity has to travel between generation and consumption is large. In long links, between large substations, a very high voltage is used to reduce the amount of electricity loss in the transportation. However, still up to 7% of the electricity is lost while transporting it to the consumers[22]. This loss of electricity is relative to the distance the electricity has to travel.

Due to the nature of generation and consumption of electricity, the network topology of the current PG is a centralized and radial topology. Where the network is setup in a tree-like fashion, the power generation is situated at the top of the tree and in each level the electricity is radiated out to a greater amount of nodes with a lower voltage than it arrived. The generated electricity is fed to the network in the highest levels of the topology with a very high voltage.

In the current situation statistical data is used to predict the amount of electricity usage. These predictions are used to reshape the power

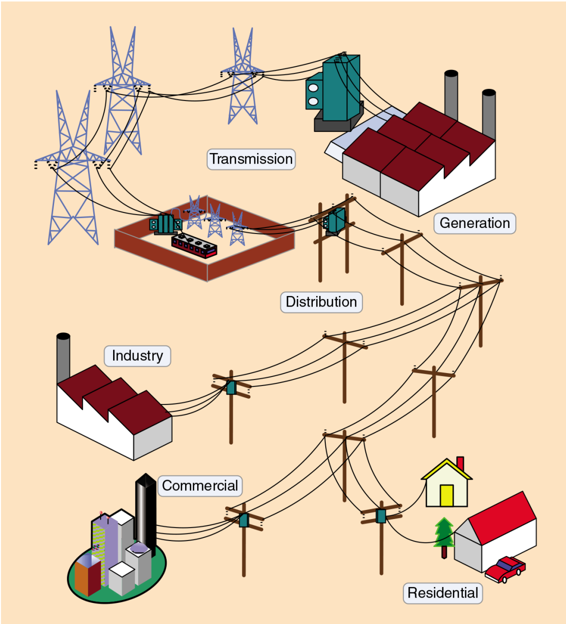

Fig. 1. The traditional PG[25].

distribution and configure distribution circuits. In case the maximum predicted load becomes too high, equipment, like transformers, has to be upgraded to ensure the PG is capable of handling the load in the near future. As the production of electricity is, in the current state, controlled by the energy company, the stability of the electricity production can be guaranteed relatively easily. Hence, the energy production can be either increased or decreased easily, as the energy company controls the production. However, when one of the main power generators fails a large portion of the PG is likely to fail, as the production can not be scaled up that fast.

To remotely monitor and control the current PG SCADA (Supervisory Control and Data Acquisition) systems are used. These SCADA systems are designed to monitor the entire PG in real-time. In the current situation the SCADA systems have to monitor a limited amount of sensors in the PG. Most SCADA systems are designed to automate the PG based on a predefined set of conditions, like increasing the power generation when the power consumption reaches an arbitrary point.

2.1 Recent developments

In the last couple of years, energy companies equipped its costumers with so called smart meters. These smart meters are at this moment primarily used for billing, so a large part of the billing process can be automated, and for collecting statistical data. This statistical data is sent back to the energy company so they can anticipate earlier on changing consumption patterns. This data is in some cases also available for customers, so they have an insight of their own usage.

Deploying own renewable energy sources, like wind turbines and solar panels, is becoming more and more affordable. Making these energy sources available for households and small-sized enterprises. This local generation of electricity can exceed the local consumption of electricity, in that case the electricity should flow back into the PG so other consumers can use that excess of electricity and the energy is not lost. The smart meters play a crucial part in this flowing back of electricity into the PG, as the smart meters can monitor the amount of electricity that is put back into the PG. This way the energy companies are able to introduce different rates, so customers can be compensated for generating more electricity than they are using with different rates for consumed energy and produced energy.

2.2 Challenges

There are several challenges regarding the current situation of the PG. Most of these challenges are strongly related to the fact that the foundations of the current PG are laid in the previous century, and the fact that the use of technology with respect to the PG has evolved rapidly in the last years.

2.2.1 Shifting consumption patterns

One of the first challenges for the PG is how the energy companies should cope with changing peak consumption. Using Plug-in Hybrid Electric Vehicles (PHEV) is one of the methods to reduce the carbon footprint, because instead of using gasoline to fuel cars PHEVs have a electric motor that drives the car. As legislation requires countries to reduce their CO_2 emissions, evolving the car fleet from gasoline powered vehicles to PHEV is encouraged by authorities. These PHEVs are charged via the existing PG, with loads ranging between 6kW and 16kW, which is often more than the peak load of households[10]. The market share of PHEVs is still quite low but shows an increasing grow in the last years[8]. In case PHEVs become the dominant choice in the automobile market, the average residential load will lay 2-3 times higher in the evening then current averages. As shown in figure 2, where the averages of Southern California are estimated by the dotted lines. The reason the dotted line starts at 17:00 is that residents charge their PHEV when they arrive home after a workday. It is clear such an increase in average load increases the stress on the PG.

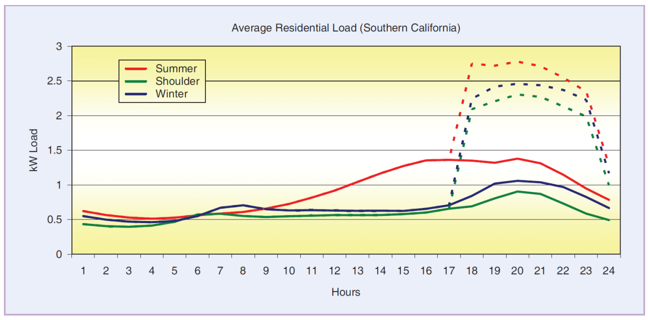

Fig. 2. Typical residential home load profile in Southern California with superimposed PHEV charging load[10].

2.2.2 Reliability and Fault tolerance

Another challenge, that has its origin in the generation of energy rather than the consumption of energy is ensuring the reliability of the PG in case more and more unreliable renewable energy sources are used to generate the needed electricity. The amount of electricity wind turbines generate is, of course, dependent on the magnitude of the wind, with too low wind speed the turbine does not produce energy and with too high wind speed the turbine has to prevent damage by disabling electricity generation. For solar panels, there is no upper limit that shuts down the solar panel, but the influence of the strength of the sun and the cloudiness does impact the amount of electricity generated by the solar panels. Fossil fuel power plants and nuclear power plants can be regulated fairly easy by feeding more material to the generator. This means that the reliability of having a certain amount of electricity available on the PG is higher when using power generated from fossil fuels. Requiring energy companies to work together with meteorologists to predict the amount of electricity that can be expected from renewable energy, so regulated power plants can increase or decrease their generation of electricity.

Besides the addition of renewable energy to the PG, the reliability of the PG has always been a challenge. In 2002 the annual costs of power outages was estimated to be around $79B in the U.S., while the total revenue of electricity was $249B[15]. These power outages are due to user error or equipment failures, but also cyber attacks on the PG can lead to power outages. This indicates how important it is to have the highest possible reliability. Smarter failure protection mechanisms should be able to create a reliable PG that predicts and prevents failures. Furthermore, the security of the grid should be airtight so attackers do not have the capability of disrupting the electricity, or at least not with a great impact.

2.2.3 Network topology

Small scale renewable energy sources that generate more electricity than locally is used will feed electricity back to the PG. This change in electricity flow should be anticipated on. The network topology should change from the centralized and radial grid to most likely microgrids, where each microgrid generates roughly the amount of electricity used in that microgrid. This means that the higher levels of topology are used only as fail-safe in case the generation of electricity is lower than the consumption. Such change in network topology leads in a reduction in transmission loss, as the transmission length between generation and consumption is shortened greatly. This is because the longer an electricity line the higher the resistance, as electricity heats up the cable, causing a loss in energy.

2.2.4 Efficiency

Increasing the efficiency of all aspects of the PG is another challenge for the current PG. The use of ICT can help increase the efficiency of all facets of the PG. By collecting more data, coming from smart meters and devices and software in the generation and distribution of electricity, algorithms can be developed that are which are better able to predict the state of the PG than current algorithms. This data can be used to adapt faster to new situations by using predictions coming from various algorithms, like machine learning algorithms. This way overcapacity can be reduced, resulting in a more efficient PG.

2.2.5 Dynamic grid

Controlling the distribution of electricity can help reduce the peaks introduced by new consumption patterns. Smart meters should be able to disable the power supply to, for example, a PHEV in case the power demand inside the house is increasing. By dynamically distributing power to appliances that do not need a constant load, the peak as shown in figure 2 can be flattened for the largest part by stretching the PHEV load not over a 5 hour interval but over 12 hours. A lot has to be done to accomplish this, as the smart meters have to know the requirements of each appliance.

To make sure the PG is future proof the grid has to be able to dynamically expand. As the state of the PG evolves over time, creating a smart grid that is solely applicable to the current state, or the state in the near future, is worthless. The infrastructure of the grid is supposed to be durable and should be operable at least a couple of decades. If there is no good plan how to let the network expand in the future, the same problem we face now will be faced in a couple of decades.

3 Implementations of a Smart Grid

To implement a real SG we need to use methods by which the system can understand the behaviors of the connected users, is reliable, efficient, and fault-tolerant. In addition the system must be locally independent in order to take action locally when it is needed. To make this happen we must use distributed control algorithms implemented in a Multi-Agent System (MAS) fashion. Furthermore, we need large data management techniques.

In this section, some implementations introduce challenges at an implementation level, which are different than the challenges stated in section 2.

3.1 Multi-Agent System Approach

MAS are distributed by design and they have three fundamental characteristics: local knowledge, flexible interactions, and bottom-up control approach [19]. Local knowledge refers to the local nature of agents which has as a result that agents only have knowledge about what they really need to know. This way the perception of the agents stays local helping reduce the amount of data that is being processed during communications. For instance, for a microgrid, an agent does not need to be informed about a small load many kilometers away. Thus a distributed MAS architecture helps implementing a scalable distribution grid.

An adjustable designed MAS is able to solve problems on its own when an unexpected event occurs. For example, a generator is disconnected. Then the MAS acknowledges that and it will be adjusted to the new circumstances. This technique is more suitable than other control methods, which must predict any faulty events that may occur in the grid. Therefore during the design of such a control method designers must predict those faulty events in order to determine the most efficient way to resolve the problems. It is obvious that predicting all possible events is very difficult. In addition, as not all events have to be known when designing the system a flexible MAS is able to expand or shrink its functionality and components without needing to completely redesign the system.

The previous two characteristics combined can implement the bottom-up control approach. This attribute is ideal for distributed systems. Agents can interact with each other and this enables different agents or even different groups of agents to co-operate. Thus tasks can be distributed and because of that, the complexity of the control system can be drastically reduced. This characteristic enables a MAS designed SG to incorporate new RE sources that work together to maintain a stable power supply. The grid could be split in many microgrids each composed of local generators, loads, and storage devices. Furthermore, groups of microgrids can be added as an intermediate level of the system. This can implement a bottom-up approach where the decisions can be taken locally instead of only centrally (see figure3.1).

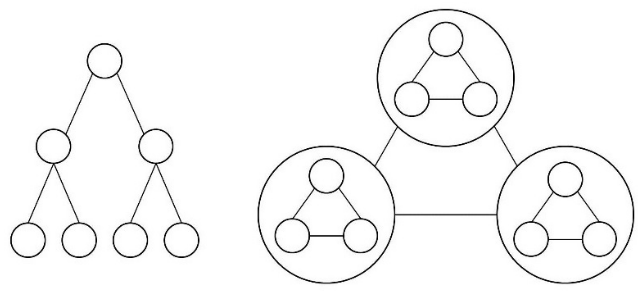

Fig. 3. One of the expected evolutions of future PGs is a change from a centralized and radial architecture (left) to a decentralized network of microgrids (right). Circles represent energy sources and loads, but also the corresponding agents.[19]

Agents should be able to retrieve information about the environment, so they are able to plan actions to fulfill their goals. This information can contain general information about the PG, but additional information from agents nearby can be requested to create a better knowledge of the environment. Agents are also supposed to be able to influence actions of other agents, by creating a social organization that valuates the influence of the agents. Having such an organization of agents reduces the amount of maintenance to the PG, as the microgrids are capable of organizing themselves and solve problems independently. This could be useful is when a microgrid is equipped with a battery to ensure the power stability. When the battery has only a small charge left, other microgrids could be asked to step in in case the battery is fully depleted. Agents can then have a vote to choose a solution, by choosing for example between the most economic friendly choice and the most reliable choice.

An important feature for the SG is the fact that MAS enables to clear communication paths between agents. As all components of the grid are implemented as agents, the communication between these components only has to be specified for agents in general. This is very helpful when creating new agents for the system, as the communication between other agents is already specified and other agents do not have to be changed to support a new agent.

3.2 Information Subsystem

To create a SG we need to generate, store, access, and analyze data efficiently in order to control the system and understand the trends and patterns of the connected users' behavior.

First of all we must be able to generate data. Data generation can be classified in two processes: smart metering, and smart monitoring and measurement [6].

3.2.1 Smart Metering

Smart metering is the most significant structure used in SG to retrieve information from end user appliances, while controlling at the same time functionalities of these appliances. Automated metering infrastructure (AMI) systems [7] are widely considered as a possible method to accomplish a SG. AMI is a mechanism that automatically obtains diagnostic, consumption, and status information from energy meters, this information is then transferred to a central database for billing, troubleshooting, and analyzing purposes. The timeliness of the data requires the information to be real-time and on demand.

Smart meters, capable of communicating with the central system, are quite similar to AMI meters and sometimes are considered as component of the AMI. A smart meter, meters the electricity consumption in predetermined time intervals, usually with intervals of an hour or less, and gives feedback to the central system for billing and monitoring purposes. Furthermore, a smart meter is able to disable and enable the power supply to appliances remotely to control loads and demands within the network of the smart meter. Figure 3.2.1 shows a way that smart meters can be used within the system. The smart meter collects the power consumption information of the dishwasher, TV, and the refrigerator, and also controls them if necessary. The data generated by the smart meters in different buildings is transmitted to a data aggregator. This aggregator could be an access point or gateway. This data can be further routed to the electric utility or the distribution substation.

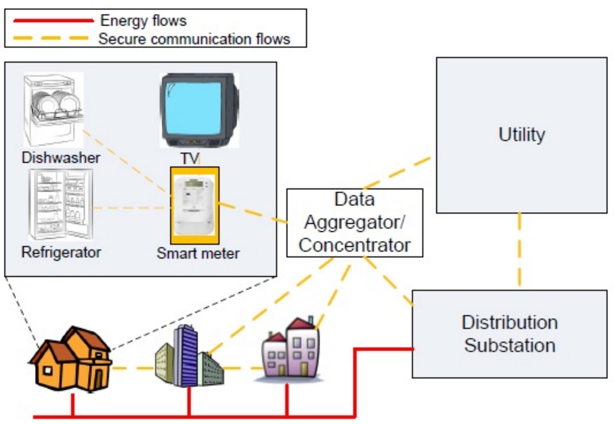

Fig. 4. An Example of the Smart Metering Structure [6].

3.2.2 Smart Monitoring and Measurment

Smart monitoring and measurement is a significant function of a SG that monitors and measures the condition of the grid. There are two main monitoring and measurements approaches: (i) sensors and (ii) phasor measurement units.

Sensors have already been used the past years as a monitoring and measurement method. Leon *et al* [12] proposed a design for assessing the structural health of transmission lines. This design improves the observability and reliability by using a two-layer sensor network of smart meters. Wireless sensor networks (WSNs) can provide a good communication platform for remote monitoring and measuring the PG. Given the low cost of WSNs this can be implemented easily and can be setup redundantly.

Phasor measurement units (PMUs) assist to create a reliable transmission network and distribution infrastructure[2]. A PMU measures the electrical waves on the power network in order to diagnose the condition of the system. With the data that is obtained by PMUs, system operators can diagnose the health of the power system and respond to system conditions in a fast and dynamic fashion.

3.3 Data Management

In a SG the amount of data that is generated from metering, sensing, monitoring is huge, so it is necessary to use an advanced data management method. The task of the data management is data storage, data modeling, data analysis, integration, and optimization.

3.3.1 Data Storage Challenges

A very challenging part of data management is the storage capacity of the systems. As the information will flow highly, there will be an increasing need in storage capacity. This is very problematic in a distributed and Multi-Agent implementation. An idea is the use of the cloud. Cloud computing enables providers to supply enormous computation and storage resources as a utility (just like electricity), rather than having to build and maintain computing and storage infrastructure for every local agent. This way there are only few huge databases stored in few central systems. In addition, this is one way to improve the information integration (integration is discussed in a later subsection) level since all information is stored and controlled by the cloud.

3.3.2 Data Modelling and Analysis

The purpose of data modeling as defined by IEEE P2030 [1], is to provide a guide to create persistent, displayable, compatible, transferable, and editable data representation for use within the emerging SG. Generally, the goal is to make the network able to exchange and use large amount of data, using proper patterns. That is especially updating the data that represents information about the grid's and smaller components' condition. This would include the majority of connected items, as they all have information about the grid's condition which may need to be shared.

Data analysis is vital to help the processing of new grid's measurements as the amount of data produced in the information subsystem is gigantic. As stated in [1], a part of the analysis can be conducted by current applications. However, there will be a need of new applications. So there is the need of experts who can implement custom-made analytic methods in an automatic system.

3.3.3 Data Integration and Optimization

The goal of data integration is to combine data that was collected by different sources, and the format of the data from different sources is likely to differ a lot. Within the SG, massive volumes of data must be combined. The first reason we need data integration, is that we have a dynamic network that is able to expand with new technologies of metering, monitoring, and measurement methods. Those new methods may have different data structures. Also new applications are created, that could be needed to process different representations of data. The second reason, is that still considerable number of utility companies do not have the ability to integrate data from different applications that are needed for system planning, energy transmission, and customer services [9], [17].

Data optimization is very important since the SG generates a huge amount of information, coming from the information subsystem, as we mentioned before. It is very likely that this information contains useless and irrelevant data. So we may need to optimize this data in order to relax the storage system and the complexity of calculations during the analysis of the data. This challenge has already been studied by lots of different researchers. Among them, Ning *et al.* [16] proposed a wavelet based data compression method in order to reduce the size of irrelevant signals and scale down white and sinusoidal noise.

3.3.4 Data Access

A very controversial subject is the the data privacy. It is always difficult to define the borders of who is sharing and owns the data. The data coming from the smart meters can be used to estimate personal information with high accuracy, according to [14]. A proposal to tackle this challenge is made by Kalogridis *et al* [11]. They proposed a system using a rechargeable battery that is placed behind the smart meter. Such battery is then used to supply some of the load that is requested from the smart meter, these request stay within the network of the smart meter and are not propagated directly to a billing operator but only when the battery has to be charged again. This system is able to hide appliance usage information, as only information about charging the battery become available for others and not information about single appliances. The ability to charge the user for the used power remains when using this system. However, increasing the privacy of users inherently decreases the power of SG, because the more information is available the better the SG can function.

3.4 Smart Demand Response

As we said in introduction a SG is a two way-flow network, a flow of electricity and a flow of information. In order to optimize the network we need to fully take advantage both flows, to achieve a smart demand response strategy. Smart demand response is considered one of the most significant aspects of the SG. Typically, electricity suppliers attempt to equalize the provided power to the demanded power. This is expensive and sometimes could be impossible. Also those tries to match the required demand could fail, and this may have as a result, blackouts, reduction in or restriction on the availability of electrical power in a particular area, and other failures. Within a SG, a smart demand response strategy must match the demand to supply and not the opposite. This could be achieved by using advanced management technologies or by persuading the users via dynamic price policies.

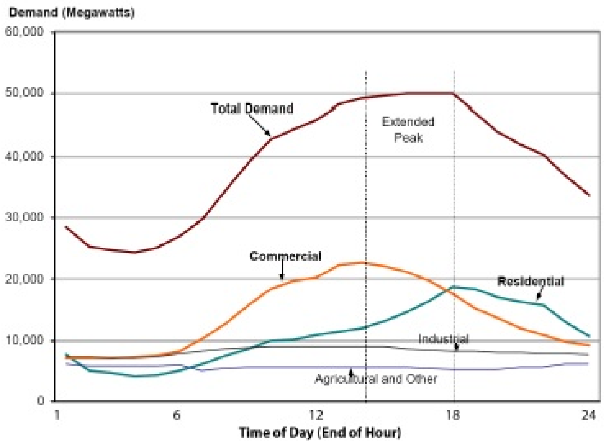

Fig. 5. Overal load profile during a warm day in California, 1991 [18].

As we can observe in figure 5 [18] the overall demand between 14:00 and 18:00 is lots of higher than the mean demand. In a SG, using smart meters and proper management strategies, energy consumption could be reduced if we turn off unnecessary devices during prime time of consumption. Therefore the total demand during peak time could be reduced.

3.5 Failure Management and Security

In a SG security measurements have to be implemented which cope with problems originating due to normal errors, like user errors and equipment failures, but also with deliberate attacks to the system. The first kind of errors are countered by a failure management system which on one hand predicts and prevents failures and on the other hand identify failures and recover from failures. The second kind of errors should be prevented by implementing smart security measurements that prevent attackers to even introduce failures.

3.5.1 Failure Prediction and Prevention

An effective approach to prevent failures is by predicting weak points in the SG. Research from Chertkov *et al.* [4] introduces an approach to identify the most probable failures for a given power network. When the normal operation mode of the SG is of a sufficient health, the failures are caused by load fluctuations at a small amount of lines. The technique they discussed can help identify the lines that are saturated the first at given scenarios. Their technique is also capable of identifying which generators are fully saturated and which generators have a capacity surplus in these scenarios.

3.5.2 Failure Identification and Recovery

As not all failures can be predicted, the SG should implement failure identification to make sure that when a part of the system fails this failure is observed in a timely manner and the system knows what exactly failed. An algorithm, developed by Tate and Overbye [20], uses known information of the system topology of the grid, together with information coming from PMUs, to detect failures on lines. To identify the impact of the outage, the algorithm is also capable of estimating the electricity flow before the failure on the failed line. In later research, again from Tate and Overbye [21], they studied how double line outages can be detected by using real-time PMU measurements and topology information before the failure happened.

Self-healing ability is very important characteristic of SG. Using microgrids that can operate autonomously prevents propagation of disturbances to other microgrids, preventing cascading events that may disrupt power supply for a large portion of the SG [13].

Smart metering increases the chance that faulty data is sent or data is missing, as the amount of sensors in a SG is far more than in the current grid. This data is vital for the correct working of the SG, so recovering of failures in smart metering is important. Research from Chen *et al.* [3] presented a B-Spline smoothing and Kernel smoothing technique that automatically cleanse faulty and missing data. This ensures that the information processing of the smart meters is not influenced by faulty or missing data.

3.5.3 Security in Smart Metering

Smart metering equipment is very attractive target for hackers, as the smart meters are already used for billing customers. Before the smart meters were deployed people physically tampered with the traditional meter, nowadays these smart meters can be reached remotely, so even physical access to the meter is not required anymore. This opens the door to attacks that can lead to shutting down the power supply to a smart meter, by requesting way to much power so that the grid automatically shuts down the power supply to prevent damage. Other attacks can involve controlling nodes, that are able to send commands to the smart meters to interrupt the power supply. This could be used in a war when most of the countries PG can be shutdown without physically attack generation, transmission and distribution assets. A method proposed by Varodayan and Gao [24] encodes redundant measurements so that it is impossible to decode the encoded messages from the encoded bits alone, which ensures the confidentiality of message.

3.5.4 Security in Monitoring and Measurement

Besides the security of smart metering, wide deployment of PMUs and other sensors could pose a threat to the SG. The measurements of these devices are typically transmitted to SCADA systems. As the SCADA systems control the PG it is very important that the received data can be trusted. So called false data injection attacks, first studied by Liu *et al* [13], are attacks to SCADA systems that introduce arbitrary errors in measurement data without being detected by existing algorithms. Using wireless communication, in the form of wireless mesh networks (WMNs), the possibility of having redundant communication paths arises which helps keeping the communication reliable. But WMNs are vulnerable to attacks, as eavesdroppers can listen to wireless messages fairly easy. Attacks to disrupt the network availability are also inherent to wireless communication, when an attacker send an overload of useless messages the normal communication can be disrupted. Khurana *et al.* discussed key design principles and engineering practices that help protocols, like DNP3 (Distributed Network Protocol), ensuring effectiveness and correctness of authentication in these protocols.

4 Discussion and Conclusion

The changes that have to be done in order to overcome the challenges of the PG will have an important repercussion to the ICT aspect. Since changes should be made in order to control, monitor, and make the system more reliable and economic. At the moment, very few uses of sensors and automation are established. These IT capabilities are very important and crucial for the SG. In the future all these techniques should be integrated to achieve a true SG.

In this paper, we have introduced some background of the PG. We have sketched the current situation of the PG and what the challenges are in evolving the PG into a smart grid. Furthermore, we have discussed some of the implementation techniques that can help or are essential for SGs. One of the greatest changes that has to be made is changing the topology of the PG, from a centralized and radial architecture the PG must evolve to a microgrid structure to fully exploit the possibilities of a SG. MAS are the most logical implementation of microgrids for SGs, where each component in the PG is an agent that is able to communicate with other agents. Also, a very important part of implementation of a SG is the information management, as huge amounts of data will be generated in order to change the PG to SG. Using those information we can predict system failures. In addition, the interconnected information network is very likely to be attacked by hackers therefore, security policies must be applied. In this literature review we tried to discuss the aspects of a SG, which mentioned before from an IT point of view.

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Providing Guidelines for Human-Centred Design in Resource Management Systems

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Abstract—In the context of residential and office buildings, resource management refers to the efficient and effective use of often limited resources, such as energy, water and heat, to fulfil user tasks. Resource management has been found to be an important tool in improving sustainability and stimulating sustainable behaviour by users.
However, the implementation of resource management systems is not a trivial task. Often, resource management systems have limitations in their design that severely limit their effectiveness. In most situations this is due to a misinterpretation of how the user will perceive information and interact with the systems, or the systems give wrong roles and responsibilities to these users.
In this research, a set of limitations will be uncovered, through literary research, on existing and emerging resource management systems that limit their effectiveness. Subsequently, a set of design guidelines will be constructed that may help prevent these issues. The results that have been found indicate that systems lack a focus on the human-centred nature of the interaction.
The guidelines include the idea that only only relevant and aggregated information should be shown to the user, using more intuitive units of measurement. Furthermore, a different approach could be taken that focuses more on changing behaviour rather than reducing consumption. The paper concludes with a summary of these results and an indication for future research.

Index Terms—Resource management (systems), sustainability, ubiquitous computing, HCI, eco-feedback, user behaviour.

1 Introduction

Resource management, in general, refers to the efficient and effective use of available and needed resources by some entity to fulfil their goals and desires. In the context of sustainable homes and office buildings, offices, or other kinds of environments, resource management may also play a significant role in promoting sustainability.

In these situations, it describes the ability of end-users to manage their consumption of resources such as energy and water, in a way that is sustainable, effective, and fulfils all of the user goals and needs as well. Resource management is inherently closely related to sustainability, as resource management often means solving problems in environments where a limited amount of resources are available, in which a sustainable approach would be preferred.

The concept of resource management (in residential and office buildings) has become a well-studied topic of research in the past couple of decades in the field of ubiquitous computing and HCI (human-computer interaction). In these environments, resource management often takes the form of in-home displays through which the user can receive feedback on their energy and water consumption levels. In some cases, they also allow the user to influence resource usage, such as by changing the temperature of a room, turning certain appliances on or off, or creating schedules for appliances to perform certain tasks at certain times of the day.

However, resource management is not limited to providing such interfaces or interaction displays. Several techniques can be used in conjunction to allow the user to perform resource management, which may result in more sustainable behaviour from the user. These techniques range from individual appliance level to the level of entire infrastructures. While the technicalities and effectiveness of these techniques are well-studied topics, the interaction between these appliances, interfaces or infrastructures on the one hand, and the users that will be using these environments on the other hand, is a relatively new research topic that does not have a trivial solution.

Often, these kind of systems will fail to perform effectively in their intended environment, due to them not being engineered with a human-centred approach in mind. This will lead to misrepresentation of information towards the user, or failing to engage the user to participate in resource management altogether. It is of critical importance to consider the effect on the behaviour of the user as well as the role of the user themselves in these new environments. To help system designers easier incorporate these considerations into resource management systems, setting guidelines for the design of such systems may be helpful. This may be necessary to ensure the most effective and successful adoption of these kind of resource management systems in sustainable environments.

In this paper, the main research goal is to describe such a general set of guidelines to stimulate human-centred design in resource management systems. Our approach is described in Section 2 of this paper, followed by a motivation for our research and an overview of the relevant terms and technologies in Section 3. Subsequently, we describe a set of limitations that we have found through our research in Section 4. In Section 5, we will give a rough and broad overview of the guidelines that we propose that may solve these problems. Finally, the paper is concluded with a summary of the results, an evaluation of our method, and prospect on future research.

2 Methodology

To arrive at the construction of the design guidelines for building effective and human-centred resource management systems, the problems of current and emerging systems will have to be uncovered first. Therefore, a range of recent researches will be considered that discuss general concepts and instances of resource management systems. Most of these papers either describe a set of use cases, along with the observations that have been made during their application in a real-life environment, or argue about resource management systems and sustainable user behaviour in general. The literature was found by critically scanning journals, relevant to this research topic, and performing a selection on these articles based on their relevance to the goal of this research.

To find intrinsic limitations of these resource management systems, we judge their ineffectiveness to fulfil the goals of a resource management, firstly in their ability to improve sustainability, and secondly in their acceptance and perceived usefulness by users and how they stimulate sustainable behaviour. Should this be a considerable ineffectiveness, and moreover if it applies to multiple of the investigated researches, we consider this as a general limitation of such systems.

We find solutions to these limitations in two ways. First of all, some researches describe some approaches themselves that could be taken

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to mitigate these issues. These approaches will be considered, along with material from supporting researches which argue about promoting sustainable behaviour by users and about human-centred design in general. According to this methodology, the researches will be investigated and a set of limitations and guidelines will be distilled.

3 BACKGROUND

This section introduces the background of the topic of resource management to the reader, particularly the forces that drive the incorporation of resource management systems into daily life and how this affects existing and emerging energy systems.

3.1 Motivation

Sustainability is a goal many individuals and companies strive to achieve to reduce their ecological footprint and to support economic and social development [4]. In this paper, we will consider resource management systems and techniques that are applicable in both of these contexts, be it residential as user living spaces, or be it business-oriented office spaces, but with an emphasis on the former of the two.

First of all, to justify research into this topic as a means of improving sustainability, it should be established that resource management is a key concept to accommodating for and stimulating sustainable behaviour by users. For example, the focus of research could solely be placed in constructing more efficient appliances that perform the same tasks as the more wasteful appliances that are already present in these homes. This would, of course, also have the potential to reduce the resource consumption of users significantly. One study reports, for example, that 30% to 50% of total energy use by ICT and consumer electronics could be saved by implementing, respectively, the most cost-effective and best technologies that were available at the time of writing, several years ago [4].

However, a research shows that the role of user behaviour in resource consumption should not be underestimated [4]. Namely, it reports that 40% of energy consumption in households can be contributed to lifestyle factors. Another comment is made on the fact that 12% of heating energy can be explained through user behaviour. Thirdly, it is suggested that 20% of carbon emissions by households can be derived back to behaviour of the inhabitants.

Similarly, the role of technological advancements regarding sustainability should not be overlooked in favour of guiding user behaviour. Study shows that efficiency upgrades to appliances or the introduction of new technologies (such as micro-generation techniques) become increasingly more important in the emerging energy systems, as a way to excite and engage the user into the adoption of sustainable values and practises [10], which will be discussed shortly.

As resource management attempts to influence user behaviour, in such a way that users are stimulated to live and work in a more sustainable way, these are significant percentages of total energy usage that could be reduced by the proper implementation of resource management. Therefore, we argue that resource management is a valuable (but not the only) tool in obtaining sustainable environments. Further on in this paper we argue that there are still limitations occurring within the implementation of resource management systems which limit their effectiveness. It is clear that guidelines need to be established that describe how resource management systems should be implemented, to help alleviate these issues.

3.2 Key Concepts

We will now elaborate on four key concepts that are vital to the successful adoption and effectiveness of resource management systems.

Human-Centred Design is described as an approach to systems design, which aims to "make interactive systems more usable, by focusing on the use of the system and applying human factors, and usability knowledge and techniques" [5]. The design showcases various characteristics related to user involvement, such as an explicit understanding of users, their tasks and environments, and that there should be consideration for the whole user experience [5]. Involvement of users should be sustained throughout design and development, and the design should be driven by user-centred evaluation. It is also an iterative design process [5].

Fig. 1. A typical IHD interface, the ecoMeter, displaying a green "safety" light [11].

Consumption Feedback refers to the ability of a system to provide accurate and real-time information to users about resource consumption levels [11, 1, 10]. Preferably, this is performed through a display or separate device which may be installed in the house or carried along by the user. Such devices or interfaces will, in the most rudimentary form, keep track of the resources being consumed in the environment of the user and report on these using some unit of measurement. End-users may then use this information, in order to make plans or perform actions to improve their sustainability.

Demand Response is another concept that is important to achieve in resource management systems (also referred to as *demand management* in literature). This refers to the ability for systems to schedule their tasks in such a way that they are executed in response to certain conditions of the resource provider, rather than immediately executing the tasks at the moment they are generated [4]. The impulse that leads to a task being executed can be any of the following: it can be triggered by a direct user command, it can be triggered by changing properties of the resource provider (e.g. responding to real-time price changes of electricity in the power grid), or it can be triggered through schedules that are set by the user (e.g. the user programs a dishwasher to turn on during nighttime).

Load-Shifting is closely related to demand response. The aim of previously described demand response systems or programs is to enable the user to transfer tasks, usually executed during peak traffic in the resource network, to periods where there is less current demand for the contested resource. This strategy is also referred to as load-shifting when viewing the entire power grid, as peaks and off-peaks in the total power consumption may be reduced in magnitude using this method [4]. An advantage of a less fluctuating level of power consumption is that the lower bound of energy generated per time-unit can be reduced, resulting in a lower overall cost for generating power. Subsequently, it also reduces the requirements of the circuiting hardware of the power grid and circuits at the buildings of the end-users for the same reason [4].

3.3 Emerging Energy Systems

Finally, before establishing the goals and opportunities for resource management systems, a description is required of the emerging environments in which the resource management systems may operate, and in which way they will manage resources in these environments. While most of the examples listed here are applied to the area of energy consumption, they can be generalised and extended to work for other types of resources, such as water, as well.

3.3.1 Current infrastructure

The current power grid is mostly a centralised network. There are any number of network nodes that directly correspond to the homes and offices of consumers, also referred to as end-users in this context, that take energy from the power grid through the appliances and technologies that they use in their environments. The consumers are connected to some facility that produces power, usually through several network links that also create a connection between them and their co-consumers. The appliances can either consume or, less prominently yet, produce energy. Resource management does have some opportunities at this level of the power grid. Namely, both consumption feedback and demand response can be implemented at the level of individual households.

In Figure 1, a so-called IHD interface is displayed, which is placed somewhere in the environment and has the ability to track consumption rates of various resources (i.e. water and energy) of the appliances in the environment [11]. In the most rudimentary form, the interface may show total consumption rates of the entire environment and provide an indication of whether this is favourable for the user, which helps the user assess their current behaviour in terms of sustainability. In some cases, these devices may also allow the user to directly intervene in their environment through the same interface (i.e. an interface for home temperature).

Demand response can be implemented at the level of individual appliances, as well as over the entire set of appliances in any environment depending on the requirements of these appliances. First of all, household equipment such as washing machines or dishwashers in most cases already possess some form of functionality that allows the user to choose at which moment in the future the pending task of the machine will be performed. Furthermore, some IHD interfaces that control temperature allow the user to submit a schedule which the system will follow during the day.

While there is already a tendency in the current infrastructure towards a situation where end-users can be both consumers and producers of energy at the same time, and contribute to the balance of resources in the power grid, this type of so-called "prosumers" is still a minority in today's power grid. Due to the lack of prosumership of users in this network, there are little opportunities for resource management at an infrastructure level [4].

3.3.2 Emergence of the Smart Grid

Right now, a transition is taking place to transform the traditional power grid into one that is more focused on residential users becoming producers of energy next to the fact that they are consumers, becoming "prosumers", also referred to as co-provisioning [4]. This is made possible due to technological advancements on the area of micro-generators, an example being photovoltaic solar cells. In these types of grids, users obtain a different role and get more responsibility with respect to energy consumption and production. Therefore, resource feedback systems should be designed in such a way that the co-provisioning role of the user is stimulated. This is the main purpose of exploring this emerging energy grid here.

The smart grid infrastructure can be described in terms of the following categories of products and services. These different products and services are also highlighted in Figure 2, which gives an overview on the levels at which these products apply and how they interact [4]:

Micro-generators: The facilities that allow residential users to produce resources, such as electricity and heat by means of photovoltaic solar cells, wind turbines or fuel cells. The behavioural effect of these facilities are that users become more aware of their own electricity production and consumption, also through the visibility of these physical devices being installed near their homes.

Storage systems: These exist both on an individual user level, as well as on a community level of multiple users. These systems temporarily store resources to compensate for a temporary lack of balance between demand and offer of resources in the local network. A similar behavioural impact is expected as instigated by micro-generators.

Smart appliances: These are the set of appliances that may be used in a sustainable home which have non-standard interfaces allowing for interaction between appliances as well as with the user. What is important here is that these devices, through intermediary devices such as IHDs, will enable load-shifting for the user. This can only be partially automated, as a level of control is needed for acceptance.

Smart meters: These are simply the IHDs or other kinds of devices which allow breakdowns of consumption levels to individual appliances. They have been shown to increase awareness of consumption levels [4].

Time variable prices and contracts: This refers to the fact that energy use now contains contextual information which can be used to support dynamic pricing and trading in a local grid. Contracts are used to support conditions (that have to be met before task execution) for tasks for individual appliances. This also supports load-shifting and reinforces shifting by showing contextual price information.

Monitoring and control systems: In a grid with real-time dynamic pricing according to demand and offer of resources, the management of consumption and tasks in such a system can become quite complex for residential end-users. This kind of management is therefore becoming increasingly more automated, while still retaining some level of control for the user. These systems will automatically react to changes in the system by executing tasks, and limiting or starting the micro-generation units for the production of energy, for example.

3.4 Resource Management Goals

Now that a foundation of the principles of resource management has been described, some intrinsic goals may be formulated that can be used to point out limitations and opportunities in resource management systems. In particular, a resource management system should (1) use resources efficiently and effectively; (2) allow the user to plan or shift consumption to moments when it is most favourable for the resource system; (3) raise awareness of users for the extents of their resource usage and creating a feeling of responsibility towards resource management; (4) stimulate and maintain sustainable behaviour by users [11, 1, 10, 4].

The role of resource management systems in the emerging smart grids should also be considered. Therefore, these systems should also (5) produce resources when favourable for the local grid; (6) trade produced resources to the local grid when not needed in the own environment [4].

4 Limitations of Existing Systems

A number of researches will now be explored which contain case studies and generic descriptions of current resource management systems, including an evaluation on their effectiveness to manage sustainability and encourage the user into adopting sustainable behaviour. Using these deficits found by these authors and our own insights from these cases, a list of core issues present in existing resource management systems will now be described.

4.1 Invisibility of Resources

Household owners are very often not aware of the amount of resources that they consume [8]. This is mainly due to the fact that household owners do not directly use resources, but instead use appliances and perform tasks that consume these resources [8]. As a result of this, resources are mostly invisible and should be made more visible to the household owners, by providing information about the resource consumption through resource management systems [6]. However, providing this information alone is not enough, as this generally does not give the proper motivation for sustainable behaviour [7] and it has only a very limited effect on the behaviour of household owners [11].

4.2 Misinterpreting feedback

The feedback that residents receive from a resource management system, through for example an IHD, can be difficult to interpret. This may be the case when, for example, the units in which the consumption is expressed is not an intuitive way for users to realise the extents of their resource usage [11]. Consumption data is often provided in abstract quantities, such as kilowatts, that assume a high expertise of the users that have to interpret the information [9] and many users have difficulty with deciding whether the amount they use is reasonable. [3]

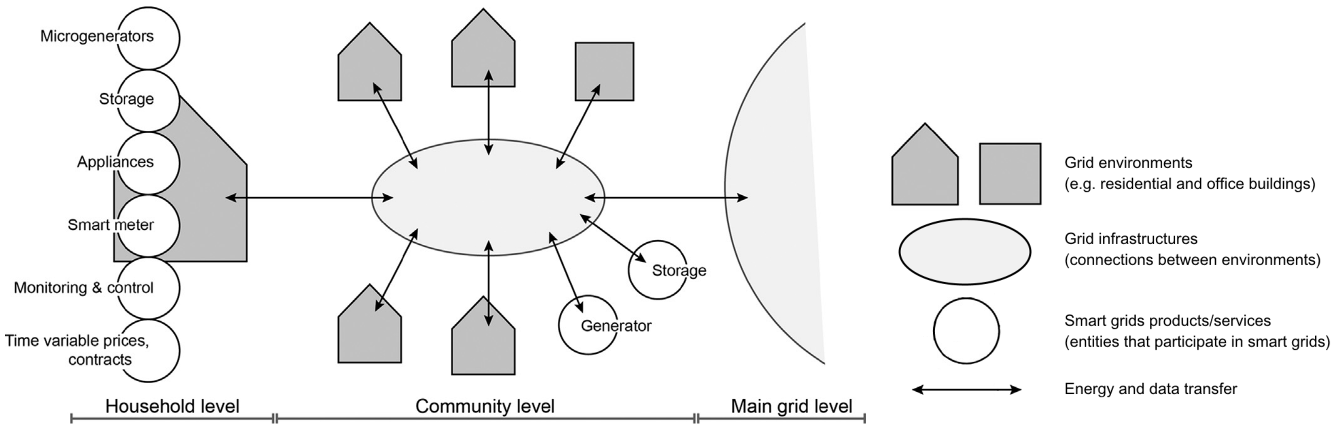

Fig. 2. Schematic overview of the categories of products and services per level that would be present in a smart grid infrastructure [4].

However, simply understanding the feedback that is being provided is not enough, because when the feedback is understood by the residents it is frequently misinterpreted. One example that makes this apparent is the indicator that can be found on IHDs that use a coloured light to indicate the amount of consumption (see Figure 1). When this light turns red, it indicates that there is a spike in resource consumption. As a result of this, residents often assume that appliances that trigger the red light are the appliances that consume the most. However, this does not have to be the case when such appliances are used infrequently or for short amounts of time. That, in turn, causes residents to overlook other appliances that do not cause these sharp spikes in consumption, but are in use for longer periods of time and thus often have a much higher contribution to consumption rates [11].

Another issue is that some of the provided feedback regards indispensable practises, which are practises that people consider necessary and unchangeable. An example occurs when the aforementioned red light is triggered when the user is boiling water. Users, in turn, do not know how to proceed with this information, because they have to boil water for their everyday activities. When feedback is provided regarding such practises, the feedback is often considered to be irrelevant since users deem that those practises cannot be omitted. This can also lead to residents ignoring the feedback that they receive altogether [11]. This indicates that, for these kind of IHD systems presented in this research, there is an inherent flaw in the approach of stimulating sustainable behaviour by users. The chosen approach may not yield any valuable results, so another approach for these kind of situations is therefore preferred.

Also, when faced with the task of conserving energy, one of the first behavioural responses of users is to turn off the lights in unoccupied rooms. This is deemed a good way of conserving energy by users. While this does reduce the overall consumption of energy, lighting does in most cases not contribute the most to the overall consumption [11]. This wasteful consumption, which is the consumption of resources when it is not necessary to do so, is also the context in which the feedback from resource management systems such as IHDs is interpreted. Because of this, the focus is mainly on reducing wasteful consumption. However, while this will definitely contribute to lowering the resource consumption, it fails to change the way in which appliances are being used [11].

4.3 Complexity introduced by technology

The technology that is introduced into a home by a resource management system can be quite complex. A highly complex system requires much effort from the user to work with the system and to use the system to be more sustainable. When the perceived effort of using the system is higher than the perceived benefit, users are not likely to change their behaviour [1].

Resource management systems can also be used to make automated decisions for users and these decisions may be based on complex logic. For this reason, the rational behind the decisions is not always clear to users. This makes it very difficult for them to adjust the technology so that it fits their needs [4].

Another important aspect of the task automation in a home is the acceptability of the technology. When many tasks are performed automatically and the user is no longer involved in those tasks, it is more difficult for users to customise the process. The trust that users have in the system can also be much lower in this case, as users perceive a decreased amount of control that they have over the system [1].

4.4 Users as micro-resource managers

Simply displaying real-time consumption rates of homes or appliances in an environment is not enough to support sustainable decision-making [11]. More often than not, IHD interfaces do operate under the assumption that household owners are so-called micro-resource managers, who approach tasks in the household rationally and weigh up the costs and benefits of performing a task at a given moment. [2]

It has been shown that showing ”raw” consumption data to end-users does have a reduction effect on energy usage (in the range of a mere 5-15%) but may only appeal to environmentally motivated people. Besides, the encouraging effects may become less prominent over time, and it is certainly not the case that users always make the most sustainable, rational decisions when approaching tasks at hand [11]. Apart from that observation, the people who are interested in the eco-feedback provided by such IHD systems are not always the people who also control the majority of consumption in a home, reducing the effect of this approach further [11].

4.5 Involvement required by co-provision

When a household also becomes a producer of electricity through micro-generation, the amount of energy that is consumed must be more in line with the amount that is being produced. This requires that households plan their tasks more carefully. For this to be effective, residents need to have insight into the production of energy [4].

This insight has to be provided explicitly to the residents through an intermediary system, because such systems are almost invisible to the residents due to the limited interaction that they have with those systems. As a result of this, a micro-generation system on its own has a very limited impact on the behaviour of residents [4].

Besides matching the supply and demand within a household, it is also possible to manage the supply and demand on a higher level. Within a community, many households can use micro-generation systems and it is possible for other households to also plan their tasks with respect to the generation of the other households within the community. However, managing this at a higher level also requires more effort from residents [4]. Another issue is that the stimuli, such as technology and financial incentives, often have a limited effect on involving the residents in co-provision [4].

5 Design Implications

In the previous section, various limitations have been exposed with respect to the majority of current resource management technologies. This section discusses implications for the design of resource management systems that are introduced to overcome many of the stated limitations. Wherever possible, we refer to other authors and research to verify that our guidelines match those found by existing literature.

5.1 Relate feedback to common concepts

In many cases, the information provided through an IHD display is presented in an abstract quantity, such as the water consumption that is being expressed in litres. For residents, the meaning of such quantities is not always clear or fully realised, which makes it difficult for these users to understand what their consumption rates mean in reality due to the unintuitive nature of these units. Analogies with more intuitive units of measurement can promote better interpretation of this consumption data by users. For example, an analogy that seems to make the water consumption more insightful, is one that relates it to buckets and bottles instead of the technical unit of litres [11].

5.2 Providing relevant feedback and context

Apart from relating IHD feedback to intuitive concepts, care should also be put in providing only the relevant feedback and context to users. For example, many solutions provide feedback based on aggregated consumption for an entire house. However, it is also possible to change appliances and let those appliances give direct feedback on the consumption, which could be more relevant to users [10].

Many techniques that exist at the moment are focused on reducing the consumption of resources, by informing users about their daily practises regarding resource usage. However, another important aspect of resource management is to include load-shifting, which is aimed more at shifting the consumption to different times rather than reducing it [10]. IHD displays and other kinds of system should provide parameters to the user that allow them and intermediary systems to make sound decisions on the topic of load-shifting. It has been shown that the consumption is shifted when variable tariffs are introduced. Residents are more likely to use appliances when prices are lower. This effect is strengthened when the residents are given feedback [4].

Finally, it may not be enough to provide users with raw consumption data related to their daily practises. When residents and systems are made aware of consumption and production patterns in their own environments, they may be more susceptible to making changes that optimise the benefits for both the end-users and the intermediary systems [4]. For example, instead of showing users the current consumption levels of appliances and other systems, users would also benefit from seeing patterns over time that show how much resources certain appliances or systems use overall.

5.3 Addressing seemingly indispensable practises

Providing effective feedback requires an understanding of the principles behind the daily practises of residents. When feedback is received regarding daily practises that are considered to be indispensable, the feedback is often ignored, as has been discussed. This is the case, because the feedback is considered obsolete or unavoidable, since those practises are deemed a necessity. However, in many cases it is possible to reduce the amount of resources that are used by those practises. For this purpose, resource management systems should be developed that support residents in changing their behaviour and thereby making those practises more efficient. In some cases, it might also be possible to challenge the underlying principles of these tasks. This could then lead to a change of behaviour, because the practise might no longer be perceived as being indispensable [11].

Another way in which these practises can be made more resource efficient, or can change the user behaviour altogether, is by influencing the behaviour through product design [12]. A product can be designed in such a way that it inherently causes the user to be more sustainable. For example, by making a washing machine use cold water by default, direct usage will be more sustainable and it requires effort to change the settings and make the product less sustainable [12] [11].

5.4 Augmenting feedback with new data

Most of the feedback that is given to residents by resource management systems is related to the amount of resources they consume. However, emerging technologies such as smart grids allow systems to record additional data about resources. For example, systems may track where and how the resource was generated, and how far it has travelled over the grid before reaching the user, such as shown in [10]. When this kind of meta-information is available to residents for the resources they use, the resources are made more tangible and it can give them the possibility to make more conscious decisions about the energy they consume, by only accepting energy that has been generated in a certain way [10].

Smart grids also allow for the introduction of dynamic pricing of resources. For this to be effective, residents and automated systems have to be informed about the current prices to enable them to adapt their behaviour to those prices. Additionally, an estimation of the prices for the near future would allow residents and systems to plan ahead their use of appliances to use them during times of low prices [10]. Related to the dynamic pricing is the information about the current network load, which must be communicated to the residents to allow them to change their use of appliances according to this load [10].

5.5 Household dynamics and roles

Research shows that practises can change in relation to past experiences, interaction with family members, peers and technology, and are therefore very volatile [11]. It is important therefore that a resource management system is capable of dealing with and adapting itself to changing user behaviour. Furthermore, to maximise perceived usefulness in household situations, eco-feedback systems such as IHDs should be as simple as possible for the residents while still providing useful feedback [1].

Another important aspect of resource management systems in households, is that they should focus specifically on the residents that have the greatest influence on the consumption and less on the people who are interested in the management of resources [11]. Currently, most IHDs assume roles of micro-resource managers, which often collides with the attitudes of the major resource users in the households, as they may not be as interested in supporting sustainable practises yet.

Insight must be provided into the operation of a smart home. This insight should help users in understanding the decisions that the smart home makes, such as when certain appliances are turned on [4]. Furthermore, aside from providing the users with information about consumption, users should also have the capability to set certain goals (e.g. ”I want to save this much energy in the next two weeks”). The system should then provide the user with feedback that explains to what extents the goal will be met. Also, changes can be proposed that may help in achieving said goal [4]. This provides for an interactive and intuitive experience that may appeal more to household situations.

5.6 Co-provisioning stimulation

Due to emerging energy grids, an important design factor in resource management systems is the proper implementation of techniques that support co-provisioning. Recall that co-provision refers to the concept where consumers are also the producers of energy at a low scale, so-called ”prosumers”. Guidelines that will enable or support the role of co-provisioning will be listed in this section.

The introduction of a micro-generation system in a household often makes the household more involved in the management of their resources [11]. However, such micro-generation systems are usually not visible to the residents because of the limited interaction with such systems. For these systems to influence the behaviour of residents, it is necessary to provide the residents with feedback about these systems and make them more visible [4].

A concept that is strongly related to smart grids, is the introduction of dynamic pricing. It has been shown that when residents are given information in such dynamic pricing systems that they are more likely to consume resources when the prices are low. On the other hand, when the prices are high and residents have surplus energy, it is possible to sell this energy back to the grid [4]. The introduction of dynamic pricing also means that residents have to be more involved in the management of their resources. It is required that they plan ahead their usage of appliances during periods of lower prices. This can require too much effort from the residents and it is possible to automate these tasks. However, since too much automation can reduce the trust that residents have in resource management systems, it is important to find a balance between on the one hand involving the resident and requiring the resident to make decisions and on the other hand performing tasks automatically [1].

Households could also sell surplus of generated energy (i.e. the superfluous produced energy that is not consumed) back to the grid. However, the emerging technologies should allow for a wider variety of decisions regarding this surplus energy [10]. For example, products and services can allow residents to manage resources on a community level and also reflect this in the feedback that is provided. This gives the residents insight into the supply and demand of the households that are part of the community and allows them to coordinate their consumption and production with the entire community [4].

Products and services should also offer residents the possibility to communicate with other households. This allows them to ask for advice on the use of energy products and also to provide this advice to other residents. It also enables residents to compare and discuss their consumption with other households and to exchange ideas for improving smart energy systems. Finally, the communication between households allows them to initiate organisational structures to facilitate a smart grid community [4]. To conclude, achieving sustainability may additionally be organised in the form of a competition or another social comparison experiment of some sort, where the behavioural patterns and the consumption or production rates of various users in a grid are put against each other. This could stimulate users into performing more sustainable behaviour in order to reach goals earlier than their friends, peers, or neighbours, and to stimulate sustainability as a topic of discussion among communities.

6 Conclusion

In this paper, guidelines have been distilled for the design of resource management systems, that may enhance the effects of sustainable techniques and may help users adopt more sustainable behaviour. Resource management systems have been defined as systems that provide one or multiple forms of insight to users and subsystems about consumption behaviour by appliances in an environment, and allow the user to influence these processes either through interfaces or by adapting their own behaviour. They are important tools for reaching sustainable environments and behaviour for current and emerging resource systems, such as the smart power grid. The key concepts and the goals of resource management systems, as tools for sustainability, have been outlined.

Part of this research included studying literature that provided case studies for resource management systems and in what regards they have failed to meet the goals of improving sustainability optimally. From these case studies, it has become clear that users are often not aware of the amount of resources that they are consuming and thus that resources have to be made more tangible. Moreover, only relevant feedback and context should be displayed to users that they can relate to through intuitive units of measurements, because otherwise they may have trouble interpreting the consumption data in the right way. Another important guideline tries to take a different angle on indispensable practises by supporting the change of behaviour of users. Finally, the study also shows that responsibility and awareness for co-provisioning is not stimulated enough by current resource management systems and to accommodate for the emerging electricity networks, co-provisioning at the individual and community level are valuable tools that have to be supported by resource management systems.

It is important to assess our approach regarding the discovery and elaboration of limitations and guidelines. We have performed a literary research on case studies of resource management systems, which led to insight on how these systems were (in)effective. This, in turn, allowed us to argue about how these systems lacked to promote user sustainability and inform the user. However, the sample size of these case studies is quite small, and the case studies were applied in various environments (home or business setting) on various scales. Therefore it is unlikely that this research touched all of the facets that limit or enlarge the effectiveness of these systems or that the results are generalisable for each resource management system. Furthermore, while our approach has rendered a series of guidelines that could detail the design of effective resource management systems, no verification of these guidelines has been performed in any way, apart from verifying our results with the references case studies and literature.

Summarising, in this research we have uncovered some limitations of current resource management systems and how they could be improved through the proposed design guidelines for a more human-centred design. This research is significant in the field, because changing consumption patterns of users and improving sustainable behaviour are difficult issues to solve, and effective resource management systems may help in these instances. The research on limitations and guidelines may however be incomplete, and more research may be needed to guarantee a proper mitigation of the pitfalls and risks of designing such systems. The intended guidelines are also not yet confirmed through practical case studies. This could also be a possible topic for future research.

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The impact of user interface design of eco-feedback systems on consumer behavior

Aurélie Fakambi and Wouter Menninga

Abstract—Saving energy in buildings and homes has become and remains a major issue for the planet. It avoids waste of irreplaceable sources of energy and decreases pollution and at the same time helps companies and households save money. For this purpose, during the last decade, systems have been developed to provide consumers with information about their energy consumption. Research has shown that the type of information displayed and the techniques used to present it have an impact on the user energy saving behavior. This raises the question about how to display the information to the consumer in a comprehensive, attractive and non-intrusive way.

In this paper, we compare and discuss the various methods of visualizing energy usage for consumers. Some of the design components of user interfaces such as historical comparisons and presentation of costs are more likely to aid in providing the consumer with an understanding of his energy usage and changing his behavior. We will extract the most effective methods from research and surveys.

The comparison of the different methods is based on results achieved in previous studies, namely the reduction of energy usage of consumers using such eco-feedback systems and the answers by such users to questions in surveys.

Little work has been done in the design of eco-feedback systems. However, the researchers in the domain (Human Computer Interface designers and environmental psychologists) agree that components such as historical comparison, presentation of costs and disaggregation by appliance are the most effective ones, even though there are no universal rules, because the context is also really important.

Index Terms—Eco-Feedback, interface design, energy consumption, consumption feedback systems, energy feedback. Human Computer Interfaces

1 INTRODUCTION

Reducing energy usage in buildings and homes still remains a major challenge. It would lead to a better environment with less pollution and waste of energy. The consumers could also save money if they adopted a more sustainable and energy efficient behavior. One method to reduce energy consumption is by increasing the awareness of consumers about their energy consumption using eco-feedback systems. These are systems with integrated sensors that provide the consumers in the building with information about their energy usage. The goal is that this leads to more energy efficient behavior by the consumers in the building.

However, research has shown that the types of information displayed and the techniques used to present it have an impact on the user behavior. For example, studies have demonstrated that the information provided must be intuitive, clear and simple and the UI attractive and not too intrusive (e.g. not too many notifications) so that the users keep using it and the system becomes integrated in the user's everyday life [10].

This means that the design of the user interface is a key factor in changing the user energy consumption behavior and raises the question of what the most effective methods to visualize energy consumption data for future eco-feedback systems are.

Our goal is to investigate the different ways to display to the users their electricity usage. Researchers and developers have selected the main design components of eco-feedback systems [6, 5]: presentation of costs, historical comparison, incentives, disaggregation by appliance and goal setting. From those components we want to extract the most effective ones, the ones which are more likely to help users saving energy.

Based on previous surveys we are going to compare the effectiveness of different eco-feedback systems by comparing the reduction in electricity usage. Additionally, we will combine the results and responses of surveys and interviews with users of such eco-feedback systems, to assess the effectiveness of different UI components.

We aim at answering many questions in our paper, related to the many decisions that have to be made when designing eco-feedback systems: **what type of data** should be displayed? and **how and how much** should the data be displayed to users?

In the first part of this paper the design components will be presented. In the second part, the surveys and studies will be elaborated on and in the third part we will present the results based on these studies and surveys.

2 ECO-FEEDBACK SYSTEM DESIGN

Developers have been implementing two different types of applications: classical eco-feedback systems and serious games (i.e. games which the purpose is not just entertainment) to make it even more attractive to the users and increase their commitment.

Important aspects of eco-feedback systems are the kind of information displayed and the method of display. However, the aesthetics are also relevant for the engagement, pleasure and interest of the user [2].

In most of the eco-feedback systems, some design components are often encountered. In this part, they are defined and later we discuss their effect on changing user behavior in order to elect the most effective ones.

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2.1 User Interface Components

The following sections describe the different UI components often used in the design of eco-feedback (ECF) systems.

2.1.1 Consumption over time

The *consumption over time* UI component is one of the most basic components. It simply displays the consumption of energy over time. Usually, several time scales can be selected, like the last few hours, days or weeks. Almost all eco-feedback systems have a component like this one [10]. An example can be seen at band 4 in Figure 1.

2.1.2 Historical & Normative comparison

Two types of comparison are often presented in eco-feedback systems: historical and normative.

Historical comparison is defined as the ability of users to view their current consumption compared to their past consumption. The historical comparison can often be displayed on a daily, weekly, monthly or yearly basis. It is used in the majority of eco-feedback systems [10], because it can be easily understood by the users, especially thanks to the use of bar charts. Observing those graphs helps reminding users of their behavior (why they used more energy this particular day for example) and in consequence aids in changing their bad habits.

However most eco-feedback systems do not take into account factors such as weather (more energy is used when it is colder) or households leaving for vacation when establishing the historical comparison [6]. This means that absolute values are analyzed whereas they should have been normalized first. Some improvements in the eco-feedback systems take those fluctuations and changes into account for more accuracy and consistency.

Another type of comparison is the *normative comparison*, which deals with comparison at a local, regional level or in a neighborhood. The effectiveness of the normative comparison comes from the fact that users are influenced by social norms and pressure. Seeing, for example, that their neighbors consume less energy than they do, should encourage them to do the same. It has been seen in previous research that such normative comparisons can lead to significant reductions in electricity usage [7, 9, 4].

2.1.3 Incentives

Incentives (rewards and penalization) allow users to earn rewards if they reduce their energy consumption or on the contrary to be penalized if they waste energy. The idea is that a system of rewards and penalization encourages behavior that leads to energy conservation and discourages wasteful behavior.

Users can be rewarded in a financial or non-financial way. Financial incentives can be, for example, credit on an electricity bill and non-financial incentives can be prizes such as an energy efficient lamp or reaching higher levels in a game. Previous research [8] has shown that incentives can result in significant reductions of the electricity consumption.

2.1.4 Disaggregation or appliance specific breakdown

Disaggregation or appliance-specific breakdown allows consumers to have a better understanding about which appliance consumes what, so it is easier for them to change a particular behavior. It helps consumers to understand the impact of the use of an appliance to answer questions like: "if I let the TV on for 5 hours, how much do I consume?". We will see in the survey part with some examples of UI that this design component is presented most of the time with pie charts and also with bar charts.

2.1.5 Goal setting

Environmental psychology departments have demonstrated that users need to find motivation in order to change their behavior [1]. Some eco-feedback systems provide *goal setting* design components. The users can set the goal themselves or they are pre-configured by the software or set by the community of users of the eco-feedback system. However, every household consumes in a different way. Therefore, households in the same neighborhood are not likely to have the same goals. One way to generate a goal setting is to compute a baseline of energy consumption based on past usage and then set the goal as some percentage reduction from the baseline. An example of a goal could be: "reduce your energy consumption with 5% compared to the previous month".

In order to motivate the users, the eco-feedback system should reward users that reach their goal and aid users to reach their goal by giving them concrete tips and advices.

2.2 Presentation of the information inside the components

When designing an eco-feedback system developers should ask themselves questions such as "what is the best and most effective way to present the information inside the design components identified in the previous part? What do the users understand easily: texts or graphs?".

Developers have several options to present the same information: text, graphs, pie and bar charts, tables etc. But each presentation will have more or less impact on the user.

Moreover, an interview conducted with an expert of the field allow us to know that the choice of colors is also really important. There should not be too many colors so that the UI stays pleasant for the eye and the designers should not use the same colors to display different kinds of information.

2.2.1 Choice of units for numerical data

The data provided to the users has to be understandable and familiar. The designers can present the energy consumption with scientific units such as: kWh (usually used in the bill), kg CO_2, Joule or using a monetary unit, like euros or environmental units such as trees saved. To make it attractive for users, some designers do not lack in originality in their choice of units for displaying the amount of consumed energy. For example, an exposition in the Bernoulliborg by ScienceLinX shows an Eco-Feedback System which displays the consumption in the units hamburgers or coffees bought.

3 The Surveys and Studies

Several studies researching the effectiveness of consumer feedback on electricity consumption have been done before. This section will describe a selection of those studies and analyze the results. The studies can be divided into two components: a user wishes component and a comparative component. We selected a wide range of surveys: some of them are theorical, while others are made in real situations or with real and available prototypes. Using different methods and approaches will allow us to have a better insight and a user-centered approach.

3.1 User wishes surveys

Several past studies have done a user wishes survey, exploring the opinions of users (generally household consumers) by asking them a set of questions.

User wishes surveys are really interesting because who else than the users can tell which elements could help them? It allows the researchers and developers to really understand what can affect and impact the user behavior.

3.1.1 Survey by Karjalainen

In a study from S. Karjalainen [6] from 2010, interviewing was used to find the best ways to present information for maximum energy reductions. In this study, interviews with consumers were held to find out about their attitude towards energy monitoring and what kind of feedback they understand and prefer.

The qualitative interviews showed that 8 out of 14 interviewees actively try to save electricity at home, while all 14 responded they want to monitor electricity consumption. The interviewees also indicated that they prefer to receive feedback via a bill, web page or dedicated wall display rather than a mobile phone.

Table 1. General questions about eco-feedback systems [6]

Question (*How important is it to...*)	Avg.
be able to compare your household's consumption to other households?	3.6
be able to compare your consumption to your prior consumption?	4.4
have a target level for consumption?	3.5
know the consumption of individual devices?	4.1
receive information on actions which would save energy?	3.9

Participants were also asked some general questions about how important they find certain aspects of eco-feedback systems. The questions were answered using a scale of 1 to 5, where 5 was very important and 1 not important at all. The questions, along with the average of the response of the 14 participants, can be seen in Table 1.

3.1.2 Own Survey

In order to have more insight/more information about what young potential users want, we conducted a survey[1] that we posted on social networks: Facebook and Twitter. The 31 respondents were aged from 16 to 26. As opposed to the other surveys discussed in this paper, we decided to target young people because it could be more efficient. Our hypothesis is that it is problably easier for them to change their bad habits compared to adults. Moreover, we could take advantage of the relation between them and technology. They are really familiar with apps and use their smartphones really often, giving an opportunity for developers to build apps and games especially for them.

First, we learnt that most of the participants (55%) want to save energy, but do not know how to accomplish this and also that a lot of respondents are unaware of the existence of eco-feedback systems (65%).

Not surprisingly, young people want an app (80%) which could either be a classical ECF system (45%) or a game (55%). They prefer graphs such as pie charts and bar charts (88%), rather than text or tables. Moreover, compared to historical comparison and presentation of costs, disaggregation by appliance (52%) is favoured by the participants. When asked if they would be more motivated to save energy if they knew how much energy their peers use, about half of them (48%) replied that they did not mind and the other half of them said it would motivate them. The respondents indicated that money is the most understandable unit for them (77%), while scientific units like kg of CO_2 were indicated to be less understandable.

In the next part we will see if the other studies and their outcomes are consistent with the results of this one.

3.2 Presentation of surveys/studies

Studies in the past have also collected data about energy consumer behavior in response to several different eco-feedback systems. These eco-feedback systems have different UI components and can therefore be used for a comparative analysis.

3.2.1 Karjalainen

In the study from S. Karjalainen [6], 8 paper user interface prototypes were developed. Table 2 shows an overview of the UI components present in these prototypes.

The prototypes were shown to consumers one by one and after showing all the prototypes, they were asked if they understood the prototypes and asked to choose the prototype they would prefer to use themselves.

The results of the survey can be seen in Table 3. Most prototypes were understood by the participants. From the results in this table, when combined with the definitions of the prototypes in Table 2 ,we can conclude that components such as: consumption in kWh, presentation of costs, disaggregation by device and table are

[1] Results are available online at http://goo.gl/eoUUoD

Table 2. Overview of information presented in the different prototypes by Karjalainen [6]

UI component	Prototype							
	1	2	3	4	5	6	7	8
Historical comparison	×							
Normative comparison		×	×					
Goal setting		×						
Consumption (kWh)	×	×				×	×	×
Power (W)				×	×			
Costs (Euro)		×				×		
Environmental factor (kg CO_2)			×					
Household total	×	×	×	×	×	×	×	
Disaggregation day/night							×	
Disaggregation by device					×	×	×	×
Chart	×			×	×		×	×
Table						×		
Other numeric		×	×		×			×
Textual			×					

Table 3. Nr of participants that understood and preferred for each of the prototypes. Total participants: 14. [6]

	Nr of participants that understood prototype	Nr of participants who preferred prototype
Prototype 1	14	1
Prototype 2	14	1
Prototype 3	8	0
Prototype 4	12	0
Prototype 5	7	1
Prototype 6	14	7
Prototype 7	13	1
Prototype 8	14	3

features/components which are easy for the users to understand. Problems with understanding were mostly due to the fact that many people are not familiar with the scientific units used and do not, for example, understand the difference between W and kWh. Secondly, people in general do not understand how CO_2 emissions relate to energy consumption. In contrast, information presented in charts and tables is understood easily by the participants.

We can conclude that units with measures such as $kgCO_2$ and text are not helpful and difficult to understand for the users.

The results of this study by Karjalainen found the following UI components most valued by consumers: presentation of costs, device-specific breakdown of energy usage and historical comparison.

3.2.2 Peschiera et al.

Research from 2010 by Peschiera et al. [7] provides more insight into the effectiveness of the normative comparison component. In their study, they tried to find out if there are differences in energy savings when participants only view personal electricity usage information versus participants also viewing average building occupant usage and usage of peers in their personal network.

To examine if such normalized comparison information motivates electricity-saving behavior, they fitted 83 rooms of a dormitory building in New York City to measure the electricity usage.

They divided the occupants participating in the study into four distinct groups:

- *Group A* – ability to view individual historical comparison with past vs. present utilization.
- *Group B* – same as group A, but with additional ability to view individual vs. average electricity usage of all other participating

occupants.

- *Group C* – same as group B, but with additional ability to view electricity usage of peers in that individual's network.
- *Control Group* – No access to electricity usage information.

Three days after the start of the study, the average electricity consumption for Group C was 34% lower than the consumption of the Control Group and 20% lower than the consumption in the period before the study. After sending the second consumption notification email, the average electricity consumption dropped to 45% below that of the Control Group (28% less than before the study). Group B only saw a significant reduction after the second notification email and Group A did not have a significant improvement.

These results show the added value of using electricity consumption data from peer networks (normalized comparison) in reducing consumers energy consumption. Building occupants that were shown data of their peers or the average usage saved more energy than users that did not receive this information.

3.2.3 R.K. Jain et al.

In another study, from R.K. Jain et al. [5], a prototype eco-feedback system was built, with five key UI design components:

- *Historical comparison* - ability to view historical electricity consumption in three modes (24h, to date and last week)
- *Normative comparison* - ability to view the average electricity consumption of friends
- *Rewards and penalization* - ability to get points or lose points based on consumption behavior
- *Incentives* - ability to redeem points for prizes
- *Disaggregation* - ability to find out the consumption of specific devices

The prototype was designed to allow users to go to any of the key design components with a single click from the main view. The system gathered and stored data on logins and use of the system in a database for later analysis.

Participants were divided into three groups: one group had access to room-level electricity usage data and consumption information of participants in their peer network added to the historical comparison graphs. The second group only had access to the room-level electricity usage data. The third group was a control group without access to the eco-feedback system.

The researchers formulated and tested three hypotheses, namely:

1. Users who reduced their energy usage relative to the control group, will have visited the eco-feedback system more often than users who increased or maintained their energy usage.
2. Users that use: historical comparison, normative comparison, incentives/rewards or disaggregation will login more than users that do not use this feature.
3. The sign of the number of reward points a user views on their first login correlates with the number of times a user will log into the eco-feedback system.

The data collected by the researchers confirmed the hypothesis that users who decreased consumption logged in more often (almost twice as often) than users with an increased consumption.

Table 4 shows the correlation between logins and use of specific design components. From these results, it can be concluded that users who used the historical comparison feature, on average logged in 3 more times than users that did not use that feature. Additionally, users that used the incentives feature, logged in more than 3 additional times compared to users that did not use that feature.

Table 4. Correlation between user logins and the use of specific design components [5]

Mean user logins by component used	Users who used feature	Users who did not use feature
Historical comparison	4.61	1.67
Normative comparison	5.00	2.40
Incentives/rewards	4.49	1.25
Disaggregation	4.60	4.00

For the normative comparison and disaggregation features, there was no significant increase in the number of logins.

With respect to the third hypothesis, they found that users who viewed a positive number of points on their first login, logged in 2.5 more times than users that got to see a negative number of points on their first login.

We can conclude based on this study that the use of normative comparison and incentives may lead to more energy savings and that emphasizing rewards over penalization may increase energy savings even more. Incentives and historical comparison also increase the engagement of users of this eco-feedback system.

3.2.4 Erickson et al.

In another paper, Erickson et al. [3] developed a city-scale eco-feedback system aimed at reducing electricity consumption. The system provided households with fine-grained feedback about the electricity usage and has incentives, comparisons and goal setting for encouragement to save energy.

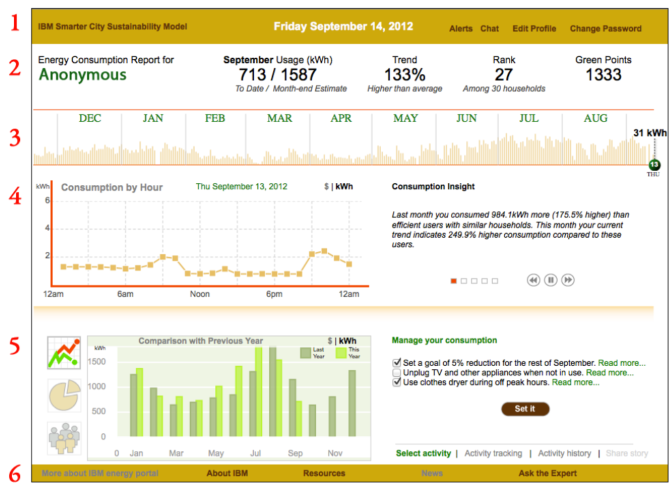

Fig. 1. The electricity portal divided in the 6 bands. [3]

The user interface of the portal can be seen in Figure 1. It is divided into 6 bands:

1. Header, with date and menu access.
2. User name, usage to date, estimate of current month's usage and three incentives: trend (for self comparison), rank (among other households) and 'green points', which can be collected with actions such as completing one's profile.
3. Daily electricity usage displayed in kWh or in dollar.
4. A graph of todays consumption and a textual comparison of the users electricity consumption.

Table 5. The UI components, ordered by popularity with the answers by participants to questions in percentages

	Usually looked at it	Was entirely clear	Helped to understand use	Encouraged to act
Consumption timeline	93%	53%	76%	49%
Consumption by hour	87%	53%	79%	52%
Comparison with previous year	87%	55%	58%	44%
Monthly usage	81%	49%	58%	45%
Consumption insights	77%	38%	46%	47%
Comparison with neighbor	67%	33%	30%	28%
Consumption by load	64%	40%	48%	31%
Trend, Rank, Points	64%	32%	41%	44%
Manage your consumption	62%	46%	34%	35%
Alerts	32%	33%	24%	19%

5. A graph allowing users to view their energy usage compared to the previous year, broken down by load or compared to 30 similar households. It also has a component where users can view and set their goals.

6. Links to general information.

The portal was made available to 765 households in a few contiguous neighborhoods in the city of Dubuque in the United States and ran for about 20 weeks. Use of the portal was logged and surveys and interviews were held to find out about the experiences of the users of the portal.

In the survey, respondents were asked to estimate how often they used the portal. The responses were as follows:

1. five or more times per week – 12%
2. about once a week – 18%
3. occasional use – 31%
4. rare use – 25%
5. not applicable / do not recall – 14%

In the survey, participants were also asked about the UI components. They were asked whether they usually looked at them, if they needed more explanation, if it helped them to better understand their electricity consumption and if it encouraged them to undertake action. The responses in percentages to these questions can be seen in Table 5.

From these results it can be concluded that the historical consumption (consumption timeline/consumption by hour) are the most popular. Also the component displaying the comparison with own prior use (historical comparison) was used often. he first four components, which are the most looked at are all time-based graphs/metrics.

All 266 participating households reduced their electricity usage. Compared to electricity consumption of the previous year, they saved on average 31,817 kWh during the project. This amounts to a monthly reduction of 3.7%. In the survey, 69% of the respondents indicated that the portal increased their understanding of how they consume electricity.

The study reports that, while the percentage of participants using the goal setting component ("Manage your consumption") is only 62%, this group of participants achieved over half of the savings. Their monthly reduction was about 7%.

3.3 Results

In this part, the results from the surveys describeb before are analyzed to extract useful information.

3.3.1 Consumption over time

The 'consumption over time' component is one of the most basic UI components for eco-feedback systems. From the study by S. Karjalainen, we can conclude that it is mostly effective when the consumption is displayed in terms of costs instead of, for example, kWh.

The study by Erickson et al. also showed that this component is the most popular and respondents to their survey indicated that this component contributed the most to understanding their energy usage.

3.3.2 Historical comparison

The 'historical comparison' component was also very popular. However, as the survey results from Erickson et al. indicate, the component is a lot less insightful to users than the 'consumption over time'.

The components also helps with increased retention, as the study by R. Jain et al. shows that this component leads to more logins of users.

3.3.3 Normative comparison

The interest from participants in the study by Karjalainen for the 'normative comparison' component was not very high. Additionally, the study from Erickson et al. found that the interest from users for this component was also not very high. Users indicated that the component did not provide much helpful information to them to aid them in reducing their electricity consumption. In the survey from Erickson, a lot of respondents said that they "were uninterested in how they compared to others".

However, the study from Peschiera et al. has found that the use of normative comparison does aid in saving more energy. This seems to be contradicting with results from the other studies and more research would be required to know more about the effectiveness of this UI component.

3.3.4 Incentives

The use of incentives/rewards & penalization, appears to be effective from the study by R.K. Jain et al., especially when it emphasizes rewards over penalizations.

3.3.5 Disaggregation

In the study by Karjalainen, one of the components most valued by consumers was the disaggregation component.

In the study by R.K. Jain et al. however, the presence of the disaggregation component did not lead to more logins. It is mentioned by them that this is not consistent with previous research. They reason that this could be due to the fact that the disaggregation component requires a lot of configuration from the user. This can be experienced by users as tedious and users might not be willing to invest such an amount of time into this UI component before being able to use it.

3.3.6 Goal setting

For the goal setting, we can conclude from the study by S. Karjalainen that people were not really interested in the goal setting component. However, this UI component does seem very valuable, because in the study by Erickson et al., the group of participants using this UI component achieved over half of the savings.

4 Discussion

In this comparative paper, the effects of the UI components in several studies are used. These studies have all taken place in different environments and during different times which makes it difficult to compare the obtained results.

The results obtained from the studies about the normative comparison are contradicting. Some studies indicate that users are not interested in this component and that it is not helpful to them, whereas other the study by Peschiera et al. obtained results that suggest that the normative UI component leads to significantly more energy savings.

Also, the study from Erickson et al. combines the UI component for incentives with a normative comparison. They reward energy saving behavior with points (which is a reward), but also use the numbers of points the user collects in a ranking, which compares all the users.

There are no universal rules when it comes to the design of eco-feedback systems. The design is also influenced by external factors, such as the environment, background/education of the users and goal of the system: saving money or taking care of the environment. An expert of the field gave us an interesting example: some building managers will not allow visitors of the building to see how much money is spent on the electricity used. The designers have to take the client requirements into account.

5 Conclusion

In this paper, we looked at different user interface components used in eco-feedback systems. Based on several studies, we conclude that problems with understanding these interfaces for consumers are often caused by unfamiliarity with the scientific units used or how CO_2 relates to electricity usage.

Out of several studies, it can be concluded that interface components that present information in charts and tables are easily understood by consumers, especially when they concern time-based graphs/metrics.

From the researched studies, we can conclude that the 'consumption over time' and 'historical comparison' UI components are generally the most popular and most insightful, especially when consumption is displayed in terms of costs.

The 'goal setting' component leads to a very significant increase in energy usage. However, the interest from users is generally low. When this component is used, it is therefore important to promote the use of it by users of the eco-feedback system.

Disaggregation is valued highly by users of eco-feedback systems. It provides much insightful and actionable information. However, a larger time to configure this component correctly, means that it is sometimes not used by consumers. This should be kept in mind when using this component in an eco-feedback system.

The use of incentives to motivate consumers to save electricity is also effective in making consumers use the eco-feedback system, especially when users of the system start with a positive number of points.

The comparison for the 'normative comparison' UI component is inconclusive and requires further research to study its effectiveness.

The previous parts and the guidelines that some eco-feedbacks systems research has established [6] allow us to extract some requirements that the UI of eco-feedback should meet in order help the developers with implementing software as effective as possible for the users.

- Sustainability and long term-commitment
- Non-intrusiveness and Acceptability
- Learnability and Intuitiveness
- Usability
- Actionable

6 Future work

Our comparative analysis showed that more research is needed to find out when the normative comparison UI component is effective and how users can be motivated to use this component.

We also saw that the goal setting is very effective, but not very popular with users. It can be helpful for UI designers of eco-feedback system if more research will be available about why the goal setting component is so unpopular and how users can be motivated to use this component.

In this comparative paper, we did not look at how interaction between users and eco-feedback systems can aid in saving more energy and this can be interesting for future work, since interaction is an important part of the interface between the system and the user.

We also did not talk about more subtle things in the UI like the use of colors (in e.g. the charts) and we did not get to a result for which device is the most appropriate, as this most likely differs per targeted user group.

During the writing of this paper we also interviewed an expert in the field to get more insight into the design of eco-feedback systems in practice. We found this interview to be useful in getting an insight about opinions related to UI components among developers/researchers. A future research could interview more people in the field to get a representative overview of opinions about UI components among developers/researchers.

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Generalized Barycentric Coordinates: A comparison of three techniques

Gerben Hettinga, Jelle Bakker

Abstract—Barycentric coordinates are a system in which a point on a simplex (a triangle, tetrahedron, etc.) is specified as the center of mass of weights coupled to the vertices of the simplex. Barycentric coordinates are uniquely defined on triangles, but not on polygons of higher order, like quadrilaterals or pentagons. Barycentric coordinates are particularly useful in interpolation over simplices and are therefore used widely in computer graphics. Generalized barycentric coordinates make it possible to use barycentric coordinates for higher order polygons. There are several techniques that define barycentric coordinates over polygons, but they do not lead to useful results in some ca Like regular barycentric coordinates, the idea is to calculate weights with respect to a vertex of the polygon and a point on the polygon.

In this paper, we compare three kinds of generalized barycentric coordinates: Wachspress coordinates, mean value coordinates and lastly discrete harmonic coordinates. These coordinates are all part of a one-parameter family called three-point coordinates.

We compare the outcomes of the techniques by looking at contour plots, which show the influence of individual vertices on the surface of the polygon. Here, two types of polygons are of interest: convex and non-convex polygons. In addition to this, we compare the effects of color interpolation over the polygon using these different types of coordinates.

Index Terms—Barycentric coordinates, Wachspress coordinates, Mean value coordinates, Harmonic coordinates, interpolation, Discrete Harmonic coordinates, polygons

1 Introduction

In this paper we will first give a short introduction to barycentric coordinates. We will mainly look at the properties that define such coordinates and what the main applications are. Then, in section 3, we will describe generalized barycentric coordinates and give an overview of three known forms of generalized barycentric coordinates, describing their definitions, how they relate to the polygon, and their advantages and disadvantages. In section 4, we will compare the outcomes of the techniques by looking at contour plots that describe the influence of individual barycentric coordinates on the surface of the polygon. In addition to this we will compare the effects of color interpolation over non-triangular polygons, such as irregular and non-concave polygons. Lastly we will compare the outcomes for non-convex polygons and see how the different coordinates behave.

2 Barycentric Coordinates

Barycentric coordinate systems were first discovered by August Ferdinand Möbius in 1827 and in his book *Der barycentrische Calcul* [1]. This system of coordinates is defined on simplices, triangles, tetrahedrons etc, and are a means to specify a point on a simplex. For a triangle barycentric coordinates are defined as weights on each of the vertices. A point on the triangle can then be defined as a unique [2] combination of these weights . There are some constraints posed on the weights. First of all the weights partition unity. This means that the weights all sum to one and when the value of two weights is known the value of the third can be derived as well. In other words, when ϕ_i represents the weight for the ith vertex then with respect to a point p inside the triangle:

$$\sum_{j=1}^{3} \phi_j(p) = 1.$$

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Secondly the value of the weights are always non-negative and smaller or equal to 1. Barycentric coordinates could be seen as a weighted average of the three vertices or as a linear combination of the vertices. To find the middle or barycentre of a triangle with vertices v_1, v_2 and v_3 we use weights $\phi_1 = \phi_2 = \phi_3 = \frac{1}{3}$. The barycentre point then is, $\phi_1 v_1 + \phi_2 v_2 + \phi_3 v_3$ or:

$$barycentre = (\phi_1, \phi_2, \phi_3)\begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix}$$

and is visualized in Figure 1 along with several other points. Thus the

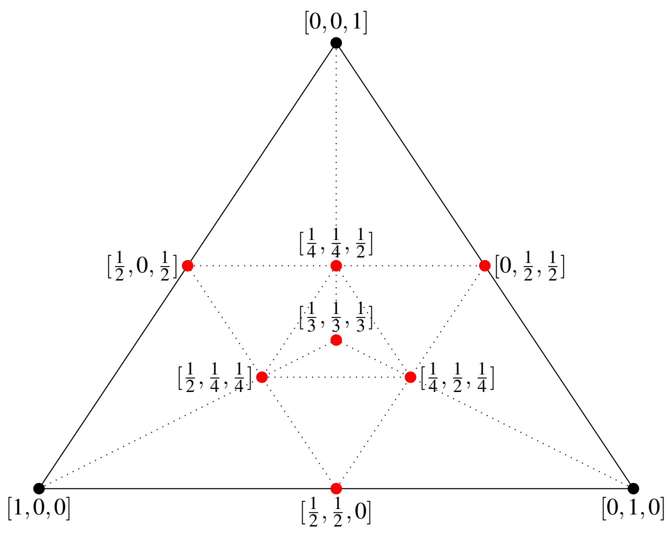


Fig. 1. Triangle in which black dots are the original vertices and the red dots are defined by barycentric coordinates.

point p is reproducible from the weights:

$$p = \sum_{j=1}^{3} \phi_j(p) v_j.$$

From this we can see that the boundary of a simplex can be expressed as a piece-wise linear function. This is due to one of the weights always being zero on the boundary. The weights satisfy the Lagrangian property: $\phi_i(v_j) = \delta_{ij}$. This property states that the weights are exactly one at the vertex they belong to and exactly zero at every other vertex. Each of the weights can be expressed as the ratio of triangle areas. The area of a triangle can be calculated using:

$$A(v_1, v_2, v_3) = \frac{1}{2} \begin{vmatrix} 1 & 1 & 1 \\ v_1.x & v_2.x & v_3.x \\ v_1.y & v_2.y & v_3.y \end{vmatrix}. \quad (1)$$

, here $A(v_1, v_2, v_3)$ is defined as the signed area of a triangle described by the three vertices v_1, v_2, v_3. Then the three barycentric coordinates can be expressed as:

$$\phi_1(p) = \frac{A(p, v2, v3)}{A(v1, v2, v3)},$$
$$\phi_2(p) = \frac{A(v1, p, v3)}{A(v1, v2, v3)},$$
$$\phi_3(p) = \frac{A(v1, v2, p)}{A(v1, v2, v3)}.$$

This shows that they are linear in p.

Barycentric coordinates can be used to interpolate values over a simplex. This is particularly useful in computer graphics, where per fragment shading is used like Phong shading [3] or per vertex shading, like Gouraud shading [4]. They can also be used in defining higher order interpolation methods like triangular Bézier patches and in finite-element methods over data that is defined on simplices.

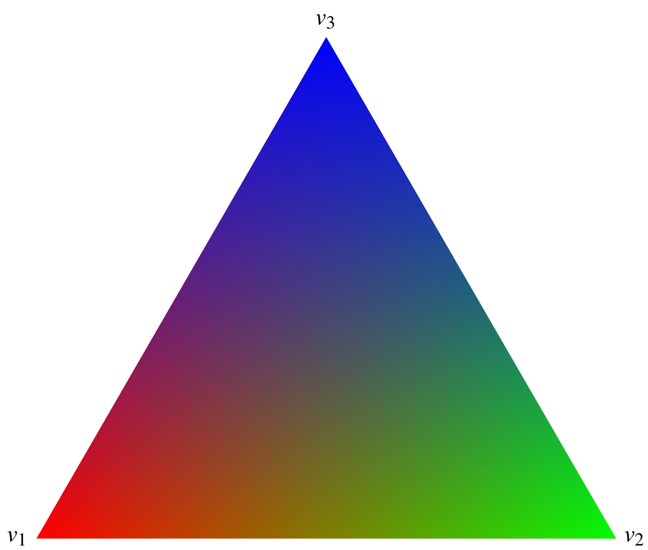


Fig. 2. Color interpolation over a triangle, using barycentric coordinates

We can define interpolation over a triangle as:

$$g(p) = \sum_{i=1}^{3} \phi_i f(v_i),$$

where f is a function defined at the vertices of the triangle. We can see that $g(v_i) = f(v_i)$ because ϕ_i is one at its corresponding vertex and for the rest of the vertices it is zero, due to the Lagrangian property. The effects of interpolation can be seen easily when using color interpolation. If all three vertices were given a different color-value (e.g. red for vertex v_1, green for vertex v_2 and blue for vertex v_3) all points in the triangle could be represented by a unique color, due to the uniqueness property of barycentric coordinates, as shown in Figure 2.

3 Generalized Barycentric Coordinates

When extending barycentric coordinates to higher order polygons like quadrilateral and pentagonal shapes and using analogous definitions, as for simplices, we find that the coordinates are not unique on these shapes. There are several ways of defining the coordinates, of which we will describe just three that are commonly used. The generalization to higher order polygons is not trivial and can be done using completely different means. Although the means are different, the same definitions that apply to barycentric coordinates, apply to generalized barycentric coordinates, regardless the way they are derived.

Barycentric coordinates can be generalized to higher-order polygons by adjusting the definitions of barycentric coordinates to:

$$p = \sum_{j=1}^{n} \phi_j(p) v_j$$

and

$$\sum_{j=1}^{n} \phi_j(p) = 1.$$

Generalized barycentric coordinates have a wider range of applications. The use of generalized barycentric coordinates in mesh articulation by constructing a cage around a mesh and then binding it to the cage is described in [5]. The mesh can then be manipulated by changing the cage structure. Not all generalized barycentric coordinate systems will produce satisfactory results in this case.

The interpolation property is also defined for generalized barycentric coordinates, which allows for interpolation of values defined at the vertices of the polygons, like normals or color values, to be interpolated over the interior of the polygon. We will explore this interpolation later on in Section 4.

3.1 Wachspress Coordinates

Wachspress coordinates were developed by Wachspress [6] and generalized to polytopes by Warren [7]. Like barycentric coordinates, Wachspress coordinates have weights that correspond to vertices on a polygon. Wachspress coordinates can be defined in two separate ways.

The first way is using areas of triangles on the polygon. A coordinate ϕ_i describing a point p on a polygon can be expressed as:

$$\phi_i = \frac{w_i(p)}{\sum_j w_j(p)}, \quad (2)$$

where $w_i(p)$ is defined as:

$$w_i(p) = \frac{A(v_{i-1}, v_i, v_{i+1})}{A(v_{i-1}, v_i, p) A(v_{i+1}, v_i, p)}. \quad (3)$$

.

It can be seen from Figure 3 how the different triangle areas are constructed. We can see from this definition that the denominator in Equation 2 is used to normalize the weights w_i.

The second way of calculating Wachspress coordinates is by using (perpendicular) distances to edges. This approach was developed by Warren [7]. By taking the normal n_i of an edge and the vector from a point p, on the polygon, to one of the vertices v_i of the edge, the distance to the edge can be determined:

$$h_i(p) = (v_i - p) \cdot n_i.$$

The other vertex on the same edge could also be taken. To calculate the weights we use Equation 2, where:

$$w_i(p) = \frac{n_i \times n_{i-1}}{h_i(p) h_{i-1}(p)}.$$

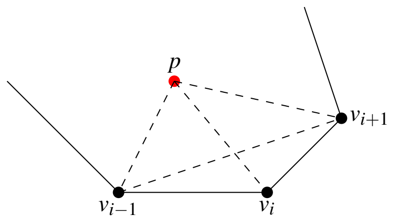


Fig. 3. The different triangles constructed with respect to p and v_i

Figure 4 shows a schematic view of the construction.

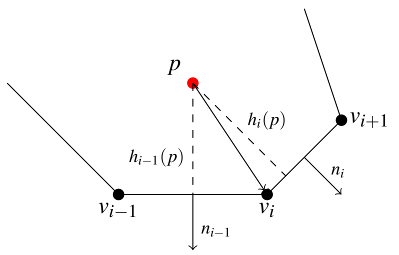


Fig. 4. The different edge distance calculations with respect to p and v_i

As becomes apparent from the definition of Wachspress coordinates they do not not allow for non-convex polygons. In [7] it is shown that this is due to the fact that the normal should always be pointing outward with respect to the edge of the polygon. When applied to non-convex polygons this could lead to negative weights. In [6] this is comparable because the signed area of triangle can be negative in non-convex shapes. When they are applied to such a polygon the weight will be come negative. Negative weights are by definition not barycentric.

3.2 Mean value coordinates

Mean value coordinates were developed by Floater [8]. Mean value coordinates are comparable to Wachspress in that they also take ratio's as defined by three coordinates.

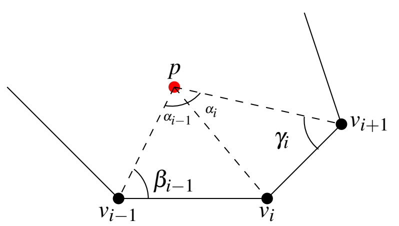


Fig. 5. The different triangles and angles constructed with respect to p and v_i

The weights per vertex are this time calculated with:

$$w_i = \frac{\tan(\alpha_i/2) + \tan(\alpha_{i-1}/2)}{||p - v_i||}, \tag{4}$$

where α_i and α_{i-1} are the angles as shown in Figure 5. The weight of the vertex is then dependent on the angle between the point relative to the polygon vertices. These angles are also defined for points outside of the polygon. Therefore mean value coordinates are also defined for the area outside of the polygon. We saw that Wachspress coordinates were limited to convex polygons. Mean value coordinates are also defined for non-convex polygons although not all weights will remain positive for points outside the polygon [9].

3.3 Discrete Harmonic coordinates

Discrete harmonic coordinates, or other times called cotangent weights, were developed by Pinkall and Polthier [10]. The coordinates are called harmonic because they satisfy the circumferential mean value property, just like the mean value coordinates.

The weights per vertex of discrete harmonic coordinates can be expressed in the form:

$$w_i = \cot\gamma_i + \cot\beta_{i-1}, \tag{5}$$

where γ_i and β_{i-1} are defined as shown in Figure 5.

We can see that these coordinates also only take into account two neighbouring vertices when calculating the weights. They are generally not well defined for points outside of the polygon as well as for non-convex shapes. This can be seen from Equation 5. This is because the weights are negative on some parts of the polygon, due to either the angle of β or γ, such that the cotangent will return negative values.

3.4 Three-point homogeneous coordinates

From the definitions of Wachspress, mean value and discrete harmonic coordinates, it follows that they all take in account three vertices when calculating each of the weights. In this section we show how these coordinates relate to each other, and how they can be generalized even further to one particular family of coordinates.

In order to explain the generic form of the earlier mentioned generalized barycentric coordinates, we first define *homogeneous coordinates*. If we find a set of functions w_i defined on the interior of the polygon, which satisfy

$$w_i(p) > 0, \quad i = 1, 2, ..., n,$$

and

$$\sum_{i=1}^{n} w_i(p)(v_i - p) = 0,$$

we call them homogeneous coordinates [11]. We define the three signed triangle areas in Figure 3 using Equation 1 as

$$\begin{aligned} A_i(p) &= A(p, v_i, v_{i+1}), \\ B_i(p) &= A(p, v_{i-1}, v_{i+1}), \\ C_i &= A(v_{i-1}, v_i, v_{i+1}), \end{aligned}$$

noting that

$$A_{i-1}(v) + A_i(v) = B_i(v) + C_i. \tag{6}$$

Let $c_1, c_2, ..., c_n$ be functions defined on the interior of the polygon. Then the functions

$$w_i = \frac{c_{i+1}A_{i-1} - c_iB_i + c_{i-1}A_i}{A_{i-1}A_i}, \tag{7}$$

are homogeneous coordinates. For a formal proof we refer to [11].

There is an alternative way of expressing w_i in Equation 7 by using the angle of the first vertex in a triangle. If we let

$$r_i(v) = ||v - v_i||,$$

and recall that $\alpha_i(v)$ denotes the angle in the triangle $[v, v_i, v_{i+1}]$ at v, then we have

$$\begin{aligned} A_i(v) &= r_i(v)r_{i+1}(v)\sin\alpha_i(v)/2, \\ B_i(v) &= r_{i-1}(v)r_{i+1}(v)\sin(\alpha_{i-1}(v) + \alpha_i(v))/2. \end{aligned}$$

From this we can derive Equation 8 and after that Equation 9 by setting $\alpha_i(v) = c_i/r_i(v)$.

$$w_i = \frac{2}{r_i}\left(\frac{c_{i+1}}{r_{i+1}\sin\alpha_i} - \frac{c_i\sin(\alpha_{i-1}+\alpha_i)}{r_i\sin\alpha_{i-1}\sin\alpha_i} + \frac{c_{i-1}}{r_{i-1}\sin\alpha_{i-1}}\right) \quad (8)$$

$$w_i = \frac{2}{r_i}\left(\frac{a_{i+1}-a_i\cos\alpha_i}{\sin\alpha_i} + \frac{a_{i-1}-a_{i-1}\cos\alpha_{i-1}}{\sin\alpha_{i-1}}\right) \quad (9)$$

We can use Equation 7 and 9 to obtain a family of homogeneous coordinates in which the different types are obtained by altering a single parameter. We do this by setting $c_i = r_i^p$, with $p \in \mathbb{R}$. By doing this we obtain

$$w_{i,p} = \frac{r_{i+1}^p A_{i-1} - r_i^p B_i + r_{i-1}^p A_i}{A_{i-1}A_i}, \quad (10)$$

which have a continuity of C^∞ within the interior of the polygon. The associated normalized functions,

$$\lambda_{i,p} = \frac{w_{i,p}}{\sum_{j=1}^n w_{j,p}},$$

are valid whenever the numerator is non-zero. Since each coordinate $w_{i,p}$ depends only on v_{i-1}, v_i and v_{i-1}, they are called *three-point coordinates* [11]. It may at times be helpful to use the angle formulation (Equation 8), which gives

$$w_{i,p} = \frac{2}{r_i}\left(\frac{r_{i+1}^{p-1} - r_i^{p-1}\cos\alpha_i}{\sin\alpha_i} + \frac{r_{i-1}^{p-1} - r_{i-1}^{p-1}\cos\alpha_{i-1}}{\sin\alpha_{i-1}}\right). \quad (11)$$

Using Equation 10 and altering p we obtain a single expression for Wachspress, Mean value and Discrete Harmonic coordinates.

If we set $p = 0$ and substitute this in Equation 10 and use the property given in Equation 6 we get

$$w_{i,0} = \frac{C_i}{A_{i-1}A_i},$$

which is equivalent to Equation 3. We can conclude that by using this family of homogeneous coordinates and setting $p = 0$ we obtain Wachspress coordinates.

We can obtain Mean value coordinates by setting $p = 1$, substituting this in Equation 11 and using the property given in Equation 6. By doing this we get

$$\begin{aligned} w_{i,1} &= \frac{2}{r_i}\left(\frac{1-\cos\alpha_i}{\sin\alpha_i} + \frac{1-\cos\alpha_{i-1}}{\sin\alpha_{i-1}}\right) \\ &= \frac{2}{r_i}\left(\tan(\alpha_{i-1}/2) + \tan(\alpha_i/2)\right) \\ &= 2\left(\frac{\tan(\alpha_{i-1}/2) + \tan(\alpha_i/2)}{r_i}\right), \end{aligned}$$

which is equivalent to Equation 4 except for the factor 2 that is cancelled by normalization.

If we set $p = 2$ and substitute this in Equation 11 we get

$$w_{i,2} = 2\left(\frac{r_{i+1} - r_i\cos\alpha_i}{r_i\sin\alpha_i} + \frac{r_{i+1} - r_i\cos\alpha_{i-1}}{r_i\sin\alpha_{i-1}}\right),$$

and by using some trigonometry we find

$$w_{i,1} = 2(\cot\gamma_i + \cot\beta_{i-1}),$$

where β_{i-1} and γ_i are the angles in Figure 5. By normalizing it is easy to see that these functions are the discrete harmonic coordinates given in Equation 5.

4 Comparison

We tested the three different types of generalized barycentric coordinates by looking at the contour plots and color interpolation for both convex and non-convex polygons. We compare the techniques by applying them to different types of polygons. We first look how well they perform on a regular, convex polygon. After that we evaluate the techniques regarding non-convex polygons and lastly another non-regular, convex polygon. We do all of this by using an OpenGL Shader Language fragment shader to shade a rectangular domain defined by two triangles. This creates a two dimensional grid on which polygons can be defined and where every pixel can be shaded individually.

4.1 Methods

We created a contour plot and an interpolation plot for every polygon-technique combination. We place a polygon on a 2D grid and then calculate for each cell on the grid, its barycentric coordinates with respect to the polygon grid-vertices.

4.1.1 Contour plot

In the contour plot we choose one of the vertices of the polygon. We then show the coordinate function of weight that corresponds to this polygon by using a banded color map to differentiate between regions in which the influence of the vertex is approximately the same. We use the banded rainbow colormap with 7 equally sized bands. This contour plot gives us good insight in how the value of a single vertex is propagated to the points of the concerned polygon. The results can be seen in Figure 6.

4.1.2 Interpolation plot

In the interpolation plot we show the influence of all the vertices of the polygon on every point of the polygon. A different color is assigned to each vertex and the colors are then interpolated over the interior of the polygon. By looking at this plot we can easily see how the different techniques perform in assigning an interpolated value to a point on a polygon and how close this is to what one would expect or would like to derive. The results can be seen in Figures 7, 8 and 9.

4.2 Results

In this section we summarize our results by giving images and comparing these images using their difference.

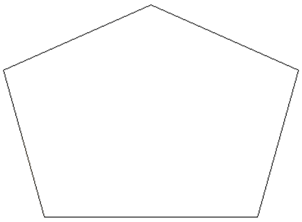
4.2.1 Convex polygon

In Figure 6 one can see the contour plots for the different techniques for a convex polygon. The colors represent the weight values regarding the vertex at the top of the polygon. Red represents high values and blue represents low values. For the Wachspress and mean value coordinates we obtain similar results as in [11].

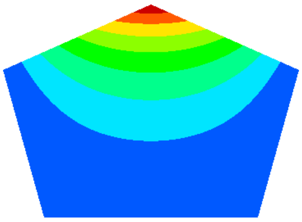
When performing color interpolation on the same convex polygon using generalized barycentric coordinates we do not see much of a difference in the results for the different techniques. The results are shown in Figures 7 and 8. It seems that the discrete harmonic coordinates is a little bit more yellow, which could be due to the fact that for the vertex that represents yellow the two neighbouring vertices have the smallest angles γ and β_{i-1} (see Figure 5) and the cotangent function is decreasing for angles between 0 and 2π. It seems that mean value coordinates produces the most differing interpolation on the polygon, whereas Wachspress and discrete harmonic seem to make one color more dominant on the interior of the polygon.

4.2.2 Irregular polygons

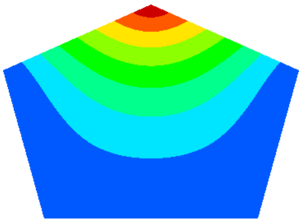
More irregular polygons will result in even bigger differences between the techniques. In Figure 9, the difference between interpolation results using Wachspress coordinates and mean value coordinates can be seen. The result for discrete harmonic coordinates was omitted, because the coordinates are either negative or not well defined on the polygon. This time the difference does not even have to be enhanced, and shows that the difference is much higher for more irregular polygons.



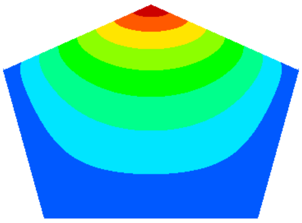
(a) Convex polygon



(b) Wachspress coordinate function

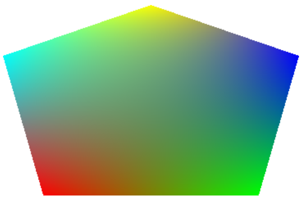


(c) Mean value coordinate function

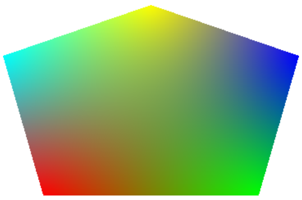


(d) Discrete harmonic coordinate function

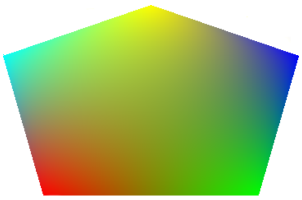
Fig. 6. Contour of convex polygon for the three different generalized barycentric coordinate techniques. Red colors mean high influence from top vertex and blue colors mean low influence.



(a) Wachspress coordinates

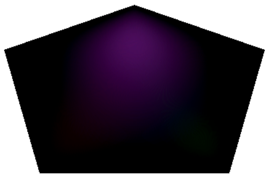


(b) Mean value coordinates

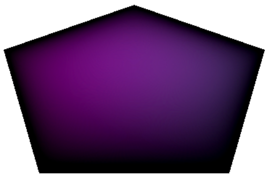


(c) Discrete harmonic coordinates

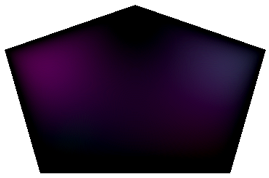
Fig. 7. Color interpolation for the three different generalized barycentric coordinate techniques.



(a) Difference between Wachspress and mean value coordinates

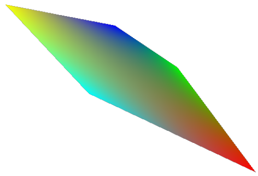


(b) Difference between Wachspress and discrete harmonic coordinates

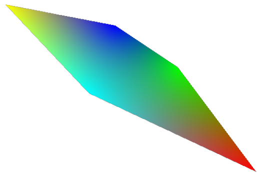


(c) Difference between mean value and discrete harmonic coordinates

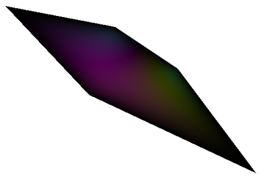
Fig. 8. Difference between color interpolations for the three different generalized barycentric coordinate techniques. Note that both the brightness and contrast are increased in order to highlight the differing regions (equally for all images).



(a) Wachspress coordinates



(b) Mean value coordinates



(c) Difference

Fig. 9. Color interpolation on a highly irregular polygon, using Wachspress coordinates and mean value coordinates

4.2.3 Non-convex polygon

When using a non-convex polygon, as visualized in Figure 10a, we see that actually only mean values coordinates lead to useful results. Both Wachspress and discrete harmonic coordinates lead to results in which parts of the polygon have negative weights. This means that the coordinates can not be called barycentric, because the weights should partition unity and not be larger than one.

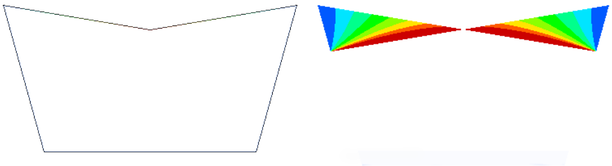
5 Conclusion

In this paper we gave a short overview of three different forms of generalized barycentric coordinates. We showed that the three different forms were very similar and could also be summarized in a single closed form expression in which only one parameter should be adapted to obtain one of the three different forms.

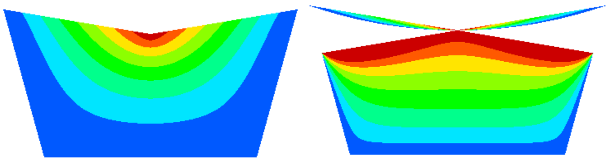
From several experiments we did with contour plots and color interpolation we could determine the strong and weak points of the different methods. Wachspress coordinates behave generally well on convex polygons but are not defined very well for non-convex polygons. Discrete harmonic coordinates only perform well on certain polygons. Mean value coordinates seem to be the best member of the three-point coordinate family, because it is well defined on convex and non-convex polygons, and therefore it is a little bit more versatile when performing for instance interpolation.

6 Future work

Barycentric coordinates are used in several methods that strive to efficiently create curved patches from regular triangles. Methods like Phong tessellation [12] or PN-triangles [13] use barycentric coordinates in the main steps of the algorithms. It would be interesting to see whether these methods can be extended to higher order polygons and what effect generalized barycentric coordinates would have on the outcome, and whether different forms of generalized barycentric coordinates will perform better or worse.



(a) Non-convex polygon (b) Wachspress coordinates



(c) Mean value coordinates (d) Discrete harmonic coordinates

Fig. 10. Non-convex polygon for the three different generalized barycentric coordinate techniques. Red colors mean high influence from top-center vertex and blue colors mean low influence.

Acknowledgements

The authors wish to thank J. Kosinka, for reviewing and consultation.

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A comparison of several room occupancy detection methods for smart buildings

Jan Kramer and Thomas Nijman

Abstract— Room occupancy detection allows smart buildings to make informed decisions to save energy and to increase user comfort. In this paper we review four different approaches to room occupancy detection. While all approaches use machine learning, the hardware used to gather the data is different in each approach. One uses a sensor network, another makes use of the smartphones occupants carry, while the last two combine the usage of smartphones with landmarks such as beacons or Wi-Fi networks. While none of the four approaches have a clear advantage in accuracy, some may be better suited by other criteria as investment cost and power usage.

Index Terms—Room occupancy detection, machine learning, sensor networks.

1 Introduction

Smart buildings and homes enable the automation of task execution, planning and resource management, which may decrease energy consumption, as well as increase comfort of their occupants at the same time. In recent years the interest in smart buildings and homes has increased, since such systems allow for more energy efficient buildings resulting in less costs and less impact on the climate.

A large portion of the power consumption of most building is due to heating, ventilation and air conditioning (HVAC) [1]. While the efficiency of the mechanical units themselves has improved dramatically over the years, there is still a lot to gain in using intelligent systems to automatically control the HVAC units. These intelligent systems could decrease power consumption and increase comfort in other ways based on the context. For example, in an office the air condition could be automatically turned on or off based on the user's presence on a hot day. Or lighting could be turned on or off based on the user's presence and the amount of daylight. The adjustment to the amount of daylight alone could result in up to 40% energy savings for lighting [3]. These improvements are possible if the location of occupants is known to the system. Therefore, the detection of room occupancy is an important issue in the context of smart buildings and homes.

1.1 Related work

Many different types of sensors have been used to detect occupancy. Some of the earlier attempts use active infrared or ultrasound tags (or badges), which can be located with sensors in the environment [14][8]. Because many sensors have to be placed around the building and tags have to be handed out, these methods are not very popular.

More recently, some methods with RFID tags have been developed. One example is the method by Ni et al [11]. In this method RFID tags are placed around the building as landmarks, which are then used to calculate the location of the RFID reader of the occupant. A disadvantage of this method is that the user has to be supplied with the hardware to read the RFID tags.

Another landmark-based approach is UnLoc [13], where the accelerometer, compass, gyroscope and Wi-Fi of a smartphone are used to locate landmarks in the building. These landmarks can then be used to compute the user location with a median error of $1.69m$. The downside of this method is that the energy usage is high, because so many sensors are used.

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One of the methods where the occupant does not have to carry anything around is described by Yu [15]. This method uses a rule-based technique on motion sensor data to detect occupants in a room with an accuracy of 80-83%, but is limited to detecting only one occupant per room.

1.2 Outline

In the Techniques section a few other room occupancy detection methods are explained. In the Results section, the testing results of all the techniques are presented. The results are discussed in the discussion section and a comparison is made based on the criteria described in the Methods section. Finally, the comparison is concluded in the Conclusion section.

2 Techniques

This chapter describes four occupancy detection methods, which are compared in section 5.

The first method [9] proposes an approach that takes advantage of the many sensors available on smartphones. This method uses audio and movement to detect occupancy and uses magnetic fields in combination with several machine learning techniques to determine the location. The second method [5] uses a combination of smartphones and Bluetooth beacons. In this case these beacons are Apple's iBeacons, which use Bluetooth Low Energy (BLE) to communicate. The location of the smartphone is determined with machine learning techniques based on signal strengths to the nearest beacons in the building. The third method [10] proposes to use data from a sensor network to correctly classify the room the user is in. This sensor network has multiple types of sensors, which are used as input for machine learning algorithms. The fourth method [2] uses smartphones and existing Wi-fi infrastructure in order to detect occupants.

2.1 Smartphone infrastructure-less approach

Smartphones have many built-in sensors, which can be used in room occupancy detection methods. Among these sensors is an accelerometer for detecting motion, a magnetometer for detecting magnetic fields and of course, a microphone. The variety of sensors allows for a wide range of room occupancy detection methods.

Khan et al [9] have proposed a method for occupancy detection by relying purely on these built-in sensors to create an infrastructure-less occupancy detection method. The system takes advantage of the above sensors to identify the number of occupants of a room. The microphone can be used on its own to infer the number of occupants using acoustic sensing. However, acoustic sensing alone is not always reliable, since it cannot detect occupants that are not engaged in a conversation. To tackle this problem, a motion sensing based counting strategy has been proposed. Finally, the room is identified with a localization technique that uses the magnetometer. Every room has a slightly different magnetic fingerprint that can be used to identify the room.

An overview of the system is shown in Figure 1. It consists of two parts, a smartphone app on the occupants smartphone and a server module. The server itself consists of two sub components: the Occupancy Context Model and the Location Context Model.

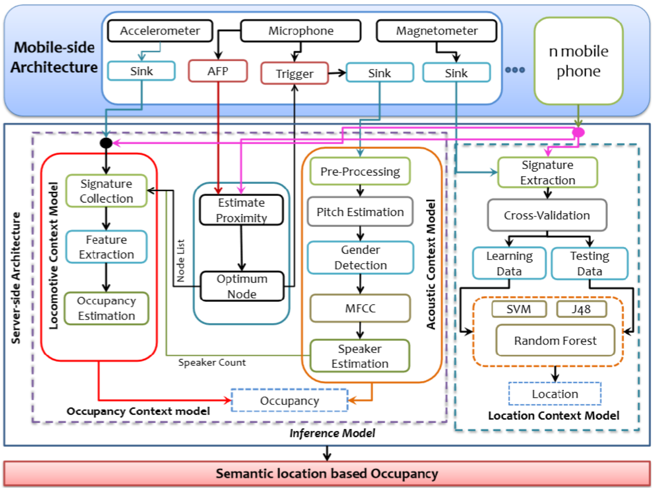

Fig. 1. Overview of the architecture of the Smartphone infrastructureless approach [9].

2.1.1 Occupancy Context Model

The occupancy context module has two sub-modules: The Acoustic Context Model (ACM) and the Locomotive Context Model (LCM).

Acoustic Context Model For counting people, the acoustic signals from the microphone are being sent through a filter to collect Acoustic Fingerprint (AFP). The smartphones then send these fingerprints to the *Estimate Proximity* module on the server. In this module the Acoustic Fingerprints are grouped based on their similarity. This allows the system to form cliques of occupants that are engaging in the same conversation. Based on signal strength, the *Optimum Node* module, assembles a sorted list of the smartphones. The list is used to elect the clique leader to record the audio data. Other smartphones deactivate their microphones in order to avoid capturing duplicate data.

The audio data from the clique leader is split into segments, each segment belonging to a specific person. Variations in pitch in the audio signal are used to distinguish different persons and to segment the audio. YIN [6] describes how to find the pitch of a segment in order to determine if it originated from a specific person. After the segmentation each of the segments is filtered using a band pass filter on the frequency range 300 Hz to 4000 Hz, which is approximately the range of human voice. For each frame of each segment, a MFCC vector and the pitch is computed. The set of MFCC vectors and pitches is now passed through the people counting algorithm, which counts the number of people using a clustering algorithm and the similarities of the segments. In the end the algorithm returns the estimated speaker count.

Locomotive Context Model The Locomotive Context Model comprises of a Signature Collection step, a Feature Extraction step and a Occupancy Estimation step.

Signature Collection receives the total number of people and the sorted smartphone list from the ACM module. Based on these two inputs, the LCM module decides if smartphone sensors are needed for further occupancy estimation. The Feature extraction module gets the accelerometer signal and feeds it into the Occupancy Estimation module that performs binary people counting as follows.

If a smartphone is stationary the onboard accelerometer sensor produces a constant signal. If there is movement, it generates a spike in this signal. In order to detect these changes in the output signal, a change point detection method is used [7]. Using Bayesian decision theory, change point probabilities are computed at discrete time points. Based on these probabilities and the audio data, the number of people present are estimated.

2.1.2 Location Estimation

Using the smartphones' magnetometer it is possible to infer the location of a smartphone. Based on the furniture and layout of a room it has a unique magnetic fingerprint. It is then possible to use machine learning algorithms to train the server to determine in which room a smartphone is located. One of the challenges in this location estimation approach is to collect ground truth data for the machine learning algorithms to use. Khan et al [9] used a crowd sourcing model to greatly ease the collection of labeled training examples.

2.2 BlueSentinel

The BlueSentinel [5] uses a smartphone in combination with beacons. The overall architecture of BlueSentinel is shown in Figure 2. These beacons are spread out over the building and send out an identification code via Bluetooth Low Energy. The smartphones use these signals to determine the beacons in range and their signal strength. Then this data is sent to the BlueSentinel Core, where a machine learning algorithm is applied to retrieve the location of the smartphone. Note that building trainer is used to train machine learning algorithms. After the machine learning algorithm classified the location, Building Management System can use this information.

2.2.1 iBeacon

The beacons used in [5] are the iBeacons from Apple, they are designed to push notifications to smartphones. Applications can get notifications when users enter or exit the range of a beacon. In addition in a short time-span after the notification the relative signal strengths of the beacons can be monitored. Since the signals cannot be monitored after these time-spans, most of the time only coarse grained location information can be derived. The following solution for this problem was proposed: If the beacons cycle between multiple identification codes, then more notifications will be generated and more accurate location detection will be possible.

2.2.2 Occupancy detection

In the BlueSentinel Core all the information regarding smartphones and beacons in vicinity and their signal strengths to each beacon are collected. Per smartphone, the signal strengths to all beacons within reach of the smartphone are used as input for a classifier using machine learning techniques. The approach used here is that of a classification problem, this way the locations of the beacons do not have to be known exactly. The machine learning algorithms used by Conte et al [5] are the K-Nearest Neighbors method and a decision trees method. Note that both machine learning algorithms require a training phase, before they can be used. In this training phase the algorithm learns how to map the beacon data to the locations of the occupant.

2.3 Multi agent sensor network occupancy estimation

BLEMS uses a multi-agent system approach with multi-modal sensors and multiple learning agents, that collaboratively learn to estimate room occupancy [10]. Sensor agents are placed in rooms to read environmental variables such as motion sensors, humidity sensors and CO_2 sensors.

2.3.1 Occupancy Estimation

Several machine learning algorithms, such as linear regression, logistic regression, multilayer perceptron and support vector machines, were used to learn room occupancy. The data set used in the training contained feature vectors and the ground truths. Since the sensors produce real-time data (in this case every minute), some preprocessing needs to be done that converts the raw data into usable values. In addition to these values the feature vector also includes the time of the day and a biasing time, which is a nonlinear function that denotes how

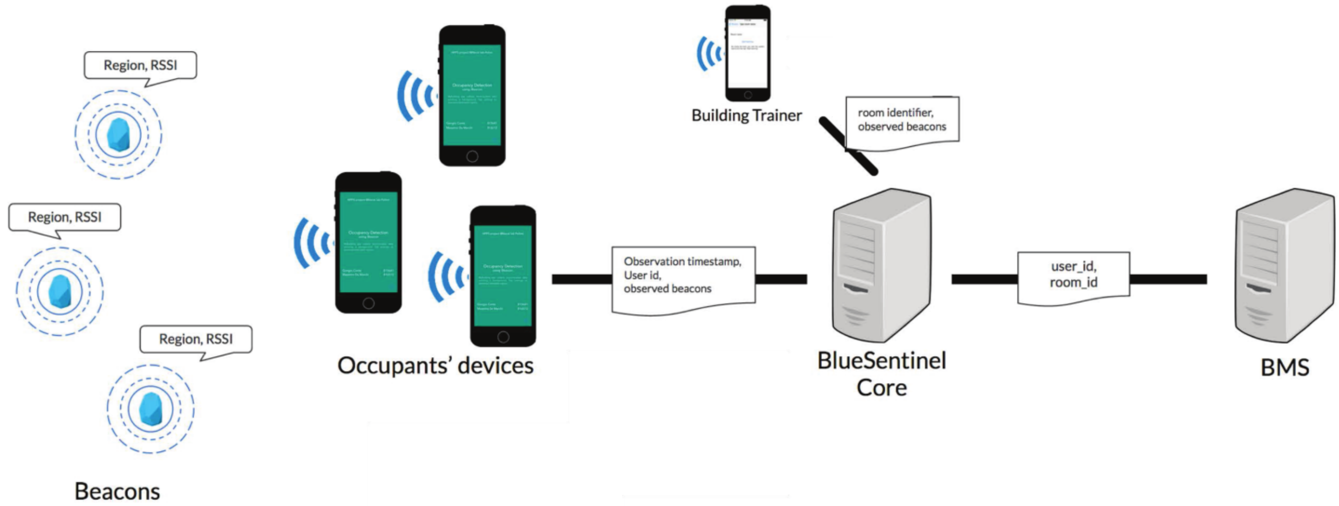

Fig. 2. The architecture of the BlueSentinel with a connection to the Building Management System [5].

likely occupants are to be in a room during work hours. In order to test the classifiers, cross validation was used with one tenth of the data set being used as test set for validation.

2.4 Wi-Fi Sentinel

Wi-Fi signals can be used to localize users using Wi-Fi devices in a building. Balaji et al[2] proposed a Wi-Fi occupancy detection method called Sentinel. This method does not use any sophisticated techniques in order to accurately localize and count users, but uses a straightforward approach that assumes that the user is in his/her space that is assigned to the the nearest access point.

3 Method

In this paper we compare four approaches to room occupancy detection. In order to make a proper comparison we defined the following criteria:

1. accuracy
2. cost / infrastructure
3. reliability
4. scalability

Accuracy depicts how often an occupancy detection method gives the correct answer in terms of occupancy detection. Detection speed depicts how much time is needed before a method can detect a user. Cost/infrastructure depicts how much time and money has to be infested before the system is operational. Reliability depicts how reliable the system is. It may seem that accuracy and reliability represent the same thing. But accuracy represents how accurate the system can be in ideal circumstances. Reliability represents how reliable the system is in general. Scalability depicts how well the method scales.

4 Results

In this section we will elaborate on some of the experimental results of the methods.

4.1 Smartphone infrastructure-less approach

The occupancy counting model was tested using four scenarios:

- No conversation among occupants
- All occupants are conversing in a single clique
- Occupants are conversing in multiple cliques
- Mixed conversing and non-conversing occupants

In scenario one, when only the locomotive counting method is used, 80 % accuracy was achieved (8 of 10 people correctly counted).

For the error measure, the following formula was used: $\frac{|EC-AC|}{N}$, where EC denotes the estimated people count, AC the actual people count, and N denotes the number of samples.

For the second scenario, experiments where done using two different phone positions: phone on the table and phone in the pocket. The results can be seen in Figure 3. The average error count observed was ≈ 0.5 with respect to the different phone positions. The occupancy estimation becomes less accurate as the distance from the clique leader to other occupants in the same conversation increases, see Figure 4. However, the error count for a 3 meter distance is close to two, which is still a reasonable result. When the number of speakers in a conversation increases, the accuracy decreases. This can be seen in Figure 5. Up until 6 people, the error remains within a constant range. When there are 7 or more speakers, the error steadily increases up until an average error of 1.7 for 10 people. But the error remains below 2, which is still a good result. For the third scenario three groups of speakers where used with group one having 5 occupants (2 men and 3 women), group two having 6 occupants (3 men and 3 women) and group three having 8 occupants (4 men and 4 women). The estimated people count versus the ground truth for each group can be seen in Figure 6. In the last scenario, where some people are talking and some are not, both the acoustic estimation and locomotive estimation are used as a hybrid method to get to the total occupancy count. For this evaluation a group of ten people was considered, where six people were engaging in conversation and four remained silent. The resulting estimated occupancy versus ground truths can be seen in Figure 7.

For the evaluation of the ocation estimation, three different machine learning algorithms where used: random forest, j48 and support vector machines. The results for the accuracy for each method can be seen in Figure 8.

4.2 BlueSentinel

The accuracy of the BlueSentinel system with K-Nearest Neighbors and Decision Trees [4] is similar with 83% and 84% respectively. Another difference between the two algorithms is that the tree approach has a slightly higher false negative rate. False negative are in comparison with false positive worse, since the user is not influenced by false positives. Also of note is that the cycling of the beacon identifiers causes missing values and that the algorithm implementations

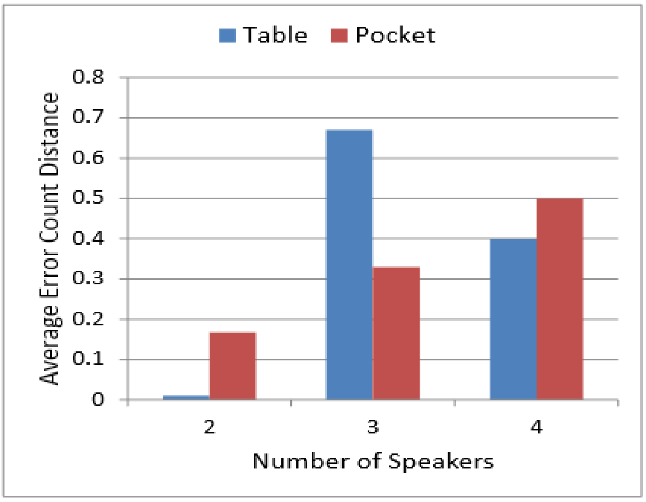

Fig. 3. Occupancy count comparison of different phone positions [9].

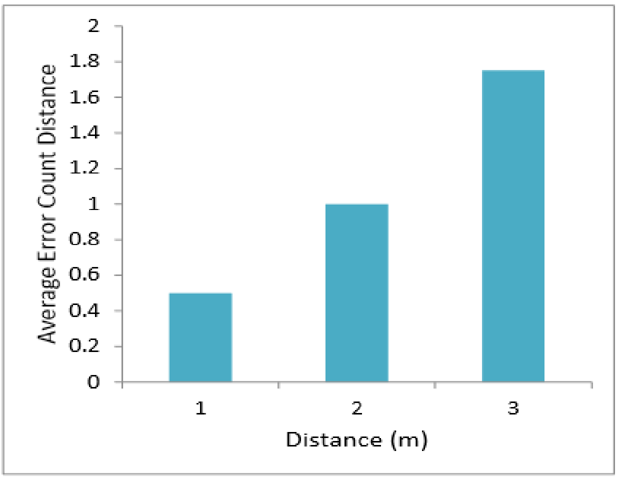

Fig. 4. People counting vs. phone distance [9].

were quite basic, hence there is still room for improvement. In general the trees approach is more promising than the K-Nearest Neighbors method, because the run-time computational cost is lower.

4.3 Multi agent sensor network approach

The occupancy can vary from zero to ten. Training data for the model was obtained over several weeks. Several machine learning algorithms were used in order to train the models. During training, cross validation was used in order to test the model. During the testing, accuracy was well above 90 % for most machine learning algorithms. Figure 9 shows the results for using a multilayer perceptron and Figure 10 shows the results for using support vector machines during a regular day.

4.4 Wi-Fi occupancy detection

This approach was able to detect occupants reasonably well, because one can link the system with personal data such as Wi-Fi authentication, authorization and accounting information. Only occupancy in personal spaces was tested, in the case this system was considered accurate about 83% of the time [2]. The impact on the battery life of the user's smartphone was also tested. Since most user's already have

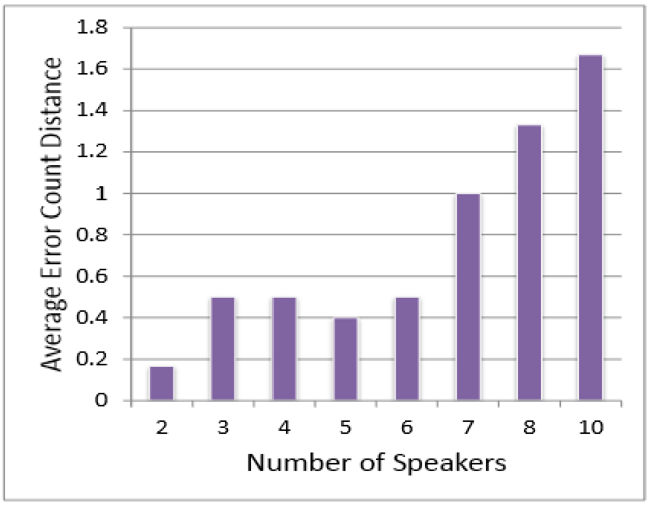

Fig. 5. Accuracy vs. number of people [9].

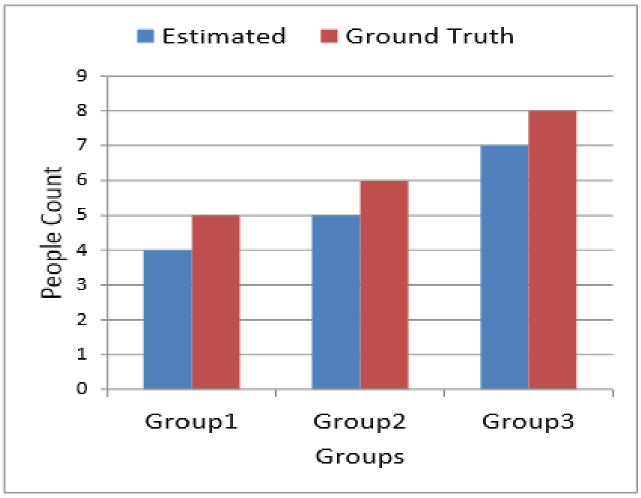

Fig. 6. Estimated people count vs. ground truth people count for each group [9].

Wi-Fi on by default, it was concluded that this method did not drain the smartphone's battery.

5 Discussion

Table 1 shows the results of our comparison. All the methods performed very well in terms of accuracy, since they give accurate results in most situations. Although it was hard to compare due to the differences in the experimental setups. The accuracy is given in terms of ideal situations. For the smartphone based methods this means that it is assumed that every user has a working smartphone and has the necessary apps installed.

The Multi-Agent Sensor Network approach requires a significant investment, since every room needs a sensor for occupancy detection. This does however make this approach very reliable, since this method does not depend much on external factors, unlike the smartphone based methods where the system relies on the smartphones of the occupants.

The smartphone sensor based method only makes use of the smartphones of the users and requires no installation/maintenance of infrastructure and therefore is low in costs. This approach has the disadvan-

	Accuracy	Cost / Infrastructure	Reliability	Scalability
Bluesentinel	++	-	+	-
Multi Agent sensor grid	++	-	++	-
Smartphone sensors	+	+	-	-
Wi-Fi Sentinel	-	++	+	+

Table 1. Comparison of the methods

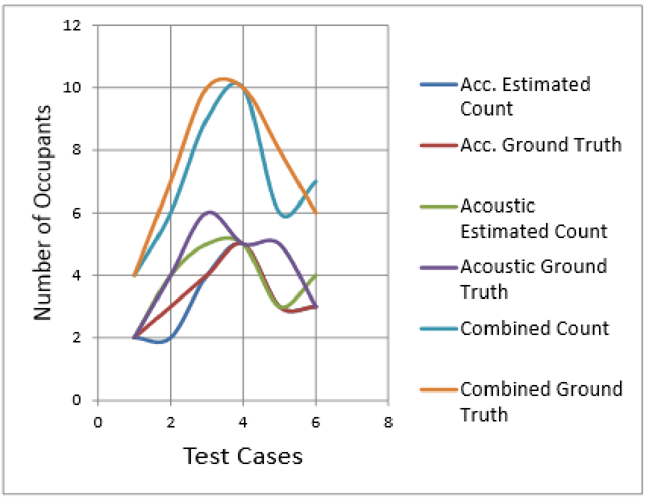

Fig. 7. Estimated people count vs. ground truths of the hybrid acoustic and accelerometer approach [9].

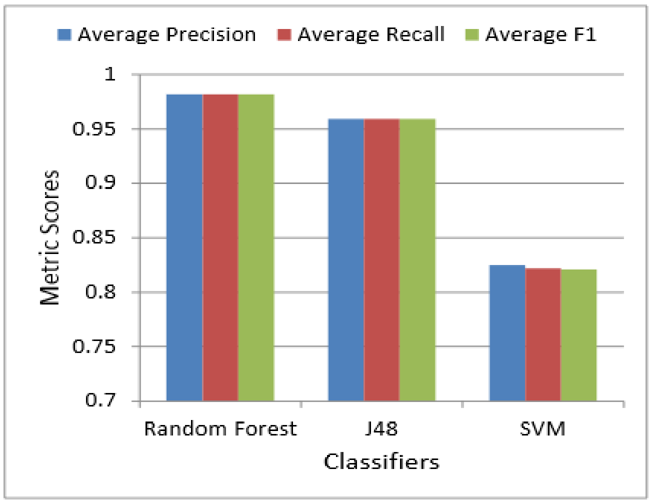

Fig. 8. Location estimator accuracy for different machine learning alforithms [9].

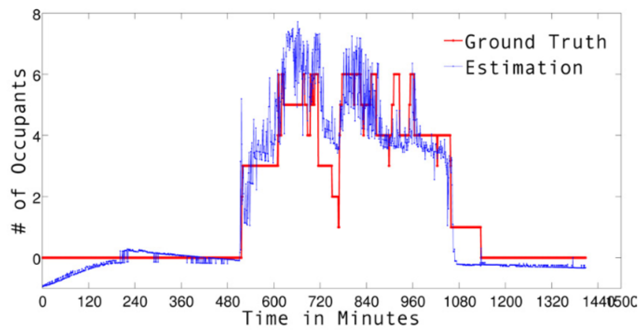

Fig. 9. Occupancy estimation using a multilayer perceptron. Courtesy of [10].

tage that users must install an app on their smartphone. Users might be worried about privacy or just do not want to install it as they do not see any personal gain in doing so. Using the sensors for a continuous amount of time drains the batteries of a smartphone[12]. Especially the microphone uses a lot of power in comparison to other smartphone sensors[12]. This problem is not solved by the selection of a clique leader and deactivation of the other phones, since the clique leaders smartphone still drains quickly. This may lead to a domino effect where more and more people remove the app from their smartphone because of a draining battery. This method is slightly less accurate than the other methods because of the factor that phones have to be able to properly record the audio signal. For instance when people have their phone in their pocket, the signal strength declines, making proper detection harder as shown in Figure 3. The distance from each speaker to his or her smartphone also plays a role, Figure 4 shows that the accuracy drops at larger distances.

The Blue Sentinel approach tries to solve the above battery problem by using a low energy variant of bluetooth. But it has the same downsides as the other smartphone based method in terms of reliability. This method still requires occupants to possess a smartphone with a required app installed. Since using bluetooth detection is significantly faster than using sensors to monitor the environment. This method is presumably faster than the previous two methods methods. although we do not have enough evidence to completely support this claim. This method also requires a significant investment in infrastructure and maintenance.

The Wi-Fi Sentinel method uses existing infrastructure, since almost all buildings nowadays have many Wi-Fi access points. This method is not very accurate and only works well in personal spaces, since it requires one access point per room if one wants to do per room occupancy detection for many rooms, but even then results are not very accurate, especially at the edges of the coverage area of an access point. Because of the fact that this method uses existing infrastructure and does not require any training time, this method is very scalable.

All the methods, except for the Wi-Fi Sentinel method, require some time in order to train the models before detection can take place. This is obviously a problem when it comes to scalability.

6 Conclusion

In this paper we described and discussed four different approaches for room occupancy detection. All methods perform well in various areas, so it is hard to pick the best method. The choice of room occupancy detection methods depends very much on the type of building and the the type of occupants. For example, in buildings where the majority of the users do not own a smartphone, an approach which does not depend on smartphones will work well like the Multi-agent sensor network approach. However with smartphones becoming more and more common this may not be a big problem in the future. Therefore the smartphone based approaches are a very interesting area for further research. One could for example try to adopt the BlueSentinel approach to Eddystone beacons introduced by Google. Or when with BlueSentinel

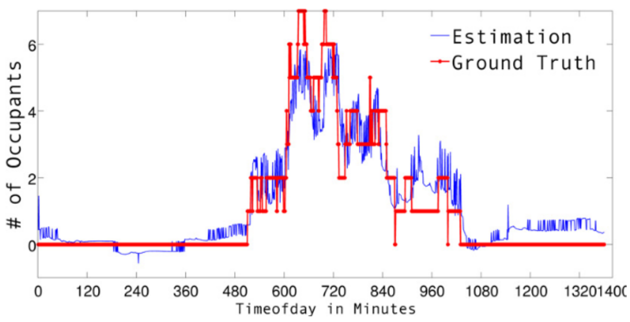

Fig. 10. Occupancy estimation using SVM. Courtesy of [10].

no notifications have recently been received, one could try to increase accuracy by using a landmark based approach with other smartphone sensors instead of cycling through beacon identifiers.

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Comparison of Digital Hair Removal Techniques

Daan Mauritsz Guus Klinkenberg

Abstract— For the correct automatic diagnostics of possible skin cancer based on images, it is important to have an good quality image without many obstructions. Most of the time, hair is an obstruction, thus several digital hair removal techniques have been developed to remove hairs from images.
In this paper several digital hair removal techniques, ranging from older techniques such as DullRazor® to new state of the art techniques such as created by Koehoorn et al. [7], are described and then compared. The results show that in general there is a trade-off between being able to remove certain types of hair, quality of the reconstructed image and time needed to run the hair removal technique.

1 Introduction

In medical practice, it is important to be able to analyze the patients skin to scan for disease and certain forms of cancer. Skin is usually covered with hair, which can make it difficult to properly analyze it. An image that only shows the skin is therefore preferred. For doctors and computer programs, it is important to get an image with the least amount of distraction and distortion as possible to deliver the best test results. Digital hair removal tries to remove the hair from an image to prevent distraction and give an image of only the skin underneath. To do this, several digital hair removal (DHR) algorithms have been developed using various techniques producing different outcomes.

Recently Koehoorn et al. [7] have published a paper that suggests a new method for digital hair removal. They did some comparisons on various techniques, but those only consists of a few sample images and no deeper algorithmic analysis. The comparison of Koehoorn et al. [7] also lacks an objective approach, where the requirements are determined before the comparison is made rather than trying to look for differences and trying to determine which one seems better without hard reasoning.

In this paper we compare the method described by Koehoorn et al. [7] with other methods and give an objective comparison between the digital hair removal methods. The methods that will be used for this comparison are DullRazor®, VirtualShave, E-shave and methods described by Abbas et al. [1] and Huang et al. [5]. For this comparison we compared the methods on time needed and accuracy when processing various kinds of hair.

We start off in section 2 with the introduction and explanation of the compared methods, after that we discuss the results of the methods in section 3. Finally the paper ends in section 4 where we take a look at the results and present the conclusion.

2 Methods

In general, digital hair removal techniques use a pipeline that consists of three steps. They first try to find where the hairs are located, then replace the color values of the pixels within the hairs to be more in line with the surrounding area, and finally smooth the resulting image. In this section we individually describe the methods that are going to be compared in this paper, being DullRazor®[8], E-Shaver[6], VirtualShave[4], Abbas et al. [1], Huang et al. [5] and Koehoorn et al. [7].

2.1 DullRazor®

Written by Lee et al. [8] in 1997, DullRazor® is one of the first techniques created to remove hairs from an image. DullRazor® has created the processing pipeline that is described earlier. It also inspired a lot of other digital hair removal programs and algorithms, that have improved one (or more) parts of the processing pipeline.

It was written with the intent to prepare images for an automatic segmentation program to seperate lesions from skin. This automatic segmentation program is easily confused by thick dark hairs and therefore the hair needs to be removed. Originally this was done by mechanically shaving the skin, but DullRazor® provides an easier, faster and software based solution for this problem.

DullRazor® introduces a three step algorithm which lays the foundation for most digital hair removal techniques. The first step is detecting the location of the hairs, then the second step is to replace the hair pixels with non-hair pixels and the third and last step smooths the image.

To detect the location of the hairs, DullRazor® first performs a morphological grayscale closing operation in horizontal, vertical and diagonal directions over the three colorbands of RGB. This allows it to process color images while retaining simplicity. The result of the closings over the different colorbands is then combined using the maximum value of the three colorbands. This image is then filtered for noise, by trying to fit a thin and long structure over it. What remains is a precise image with hair locations.

Next, the hairs will be taken out of the picture, by replacing the color value of those hair pixels with interpolated values based on pixels that are not part of a hair using bilinear interpolation.

To smooth the image, DullRazor® performs dilation and median filtering using 5x5 masks that are completely filled with ones. These are only applied to pixels inside of recognized hair regions.

The DullRazor® method has been applied to an image and the result of this is displayed in Figure 1.

2.2 E-shaver

E-shaver, written by Kiani and Sharafat [6] in 2011, is a digital hair removal method that improves on the well-known DullRazor® method. It has the ability to detect and remove both light and dark colored hairs regardless of thickness of the hairs; this is an improvement on DullRazor that is limited to removing thick dark hairs. E-shaver follows the same steps as DullRazor. First it detects the hair, then replaces the hair pixels with non-hair pixels and as the last step smooths the final result.

E-shaver makes use of 2 different Prewitt filters to detect hairs. The first filter is a normal 3x3 filter (H_1 as found in Structuring Element 1), the second one is a stretched 3x5 filter (H_2 as found in Structuring Element 2).

$$H_1 = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \\ -1 & -1 & -1 \end{bmatrix} \tag{1}$$

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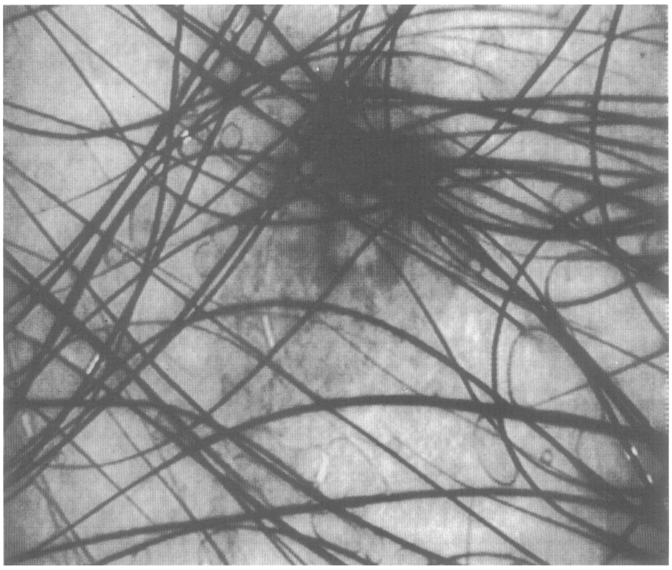
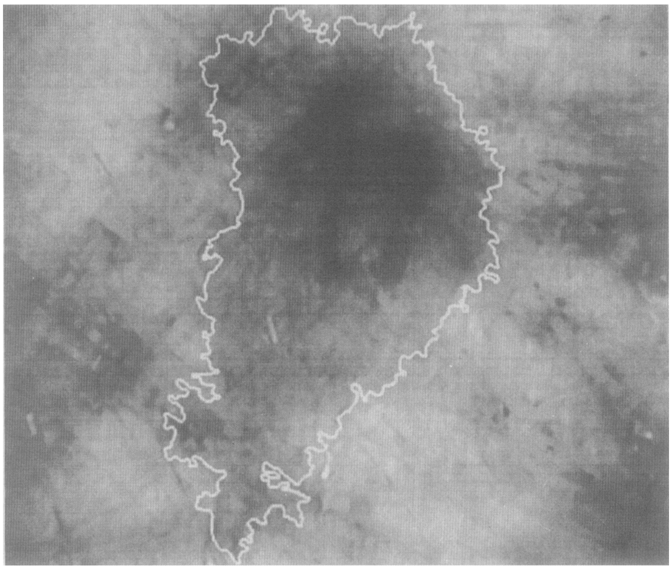


(a) Image of lesion covered by thick dark hairs before DullRazor® has been applied. From Lee et al. [8]



(b) Image of Figure 1a after DullRazor® has been applied. From Lee et al. [8]

Fig. 1: Before and after of an image processed by DullRazor®

$$H_2 = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ -1 & -1 & -1 & -1 & -1 \end{bmatrix} \quad (2)$$

The method either uses H_1 and H_2 masks, or the transposed versions, based on the predominant orientation of the hairs. This orientation is obtained by performing the Radon transform (as defined in Kiani and Sharafat [6]). After filtering the image it is thresholded to produce a mask that contains thin structures. E-shaver uses a 13x13 matrix with single width pixel lines in different directions to threshold the image. This results in two masks (one for H_1 and one for H_2) with the locations of the hairs. These masks are combined into one final mask which is used for replacement and smoothing.

The replacement of the hair pixels with non-hair pixels is done by using interpolation. First E-shaver creates a copy of the input image where all the hair pixels are replaced by the value of the average gray level of the background. Then several averages are calculated on the image by using a 3x3 window. After 3 iterations the resulting image is multiplied by the mask. By repeating this process all hair pixels get new values. The values of the hair pixels are then inserted into the original image to obtain a hairless picture.

The smoothing step is not necessary in the E-shaver method and can be skipped to avoid possibly damaging the background. It can be executed by averaging to remove the remaining background of the hairless image.

In Figure 2 an example execution of e-shaver is displayed.

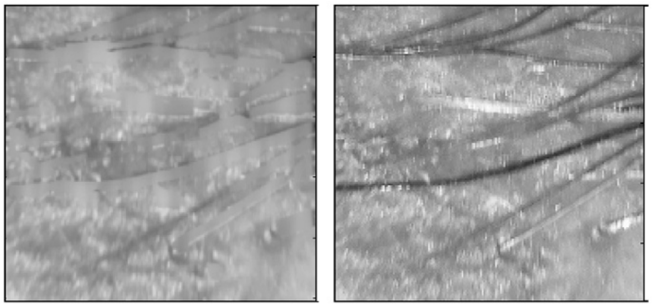


Fig. 2: Image after (left) and E-shaver has been applied. Source : Kiani and Sharafat [6]

2.3 VirtualShave

VirtualShave, written by Fiorese et al. [4] in 2011, is a digital hair removal technique that differentiates a bit from the three steps introduced by DullRazor® that most digital hair removal techniques use. VirtualShave exists of only two steps, beginning with segmentation followed by inpainting. These two steps corresponds with the hair detection and pixels replacement steps of DullRazor® where the goal of the segmentation step is finding the hair locations and the inpainting replaces hair pixels for non-hair pixels.

VirtualShave implements segmentation by using a closure based top-hat filter to detect contrasted objects on non-uniform backgrounds. It uses eight structuring elements for this operation. These structering elements are 13 pixels long in the different orientations of 0, 45, 90 and 135 degrees both one pixel and two pixels in width. This operation is done on the three color channels red, blue and green on a color image and just once on a grayscale image. After the top-hat filter VirtualShave uses a decision tree for false positive removal since there is usually a lot of noise in the resulting image. Each area of detected hair travels through the decision tree which removes each region whose shape is geometrically incompatible with hair. Then VirtualShave goes through hair fitting, a false negative removal process. It is possible for thin and light hairs to result in a few unconnected regions rather then one connected one. Fair fitting tries to find such regions and connect them to each other, resulting in a hair mask which should be rather accurate.

After the segmentation process VirtualShave uses PDE-based inpainting [2] to replace the hair pixels with non-hair pixels. An example of the final result of the VirtualShave application is displayed in Figure 3.

2.4 Abbas et al

The technique proposed by Abbas et al. [1] in 2011 uses three steps, first it detects hairs with the use of a derivative of Gaussian (DoG) then refines this by morphological techniques and the last step is hair repair by fast marching inpainting. This method focuses on the cases where dark hair is displayed on a dark background and tries to perform in this area. A step by step explanation of the algorithm is given below:

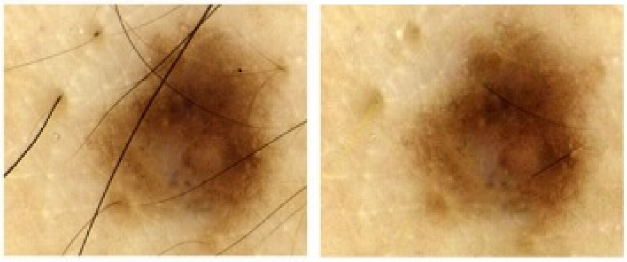


Fig. 3: Image of before and after VirtualShave has been applied. Source : Fiorese et al. [4]

The first step is the initial detection of hairs, this is done by filtering with a derivative of Gaussian. This derivative of Gaussian can efficiently detect lines regardless of orientation. A mask is created of all the detected hair pixels.

To refine the image, the mask connects all hair regions that are 10 to 20 pixels apart from each other and connects them for an experimental dataset. Then the algorithm uses a morphological area-opening function along with a condition where borders can not be circular, which results in a new mask with hair pixels. To obtain smooth hair lines the mask is subjected to two more morphological operators, dilation and filling to get a final smooth mask.

To replace the hair pixels with non-hair pixels this method uses a fast inpainting method by Bornemann and März [3] and improves on it to make it more representative of the human perception. The result is displayed in Figure 4.

Fig. 4: Image displaying the Abbas et al. propesed algorithm. Source : Abbas et al. [1]

2.5 Huang et al.

The technique made by Huang et al. [5] is based upon DullRazor® and is equal in the replacement and smoothing part. However, it differs in the way it detects the hairs.

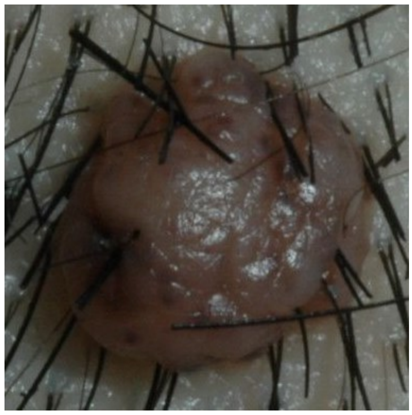
Where DullRazor® used closures of images to detect hairs, Huang et al. [5] used matched filtering instead. Matched filtering is a technique to convolve an image to find similar patterns in the image. The reasoning behind this change is that it works great to find blood vessels on skin images and hairs have a sort of similar appearance. After the matched filtering has taken place, the image is thresholded and a Canny edge detector is used to extract hair locations.

2.6 Koehoorn et al.

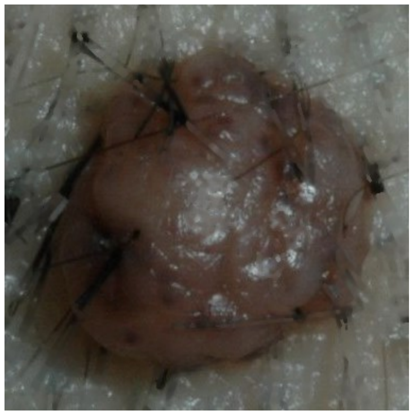
This method is the method that is the least like DullRazor® as it does not incorporate any of its original methods. Koehoorn et al. [7] does work with a similar process pipeline but shortens it because it does not need smoothing.

The goal of the method described by Koehoorn et al. [7] is to keep as much information as possible, while still being able to detect hairs with a lot of variance in thickness, color or contrast in one image. To do this it first decomposes the image based on luminance level of the HSV representation of the image.

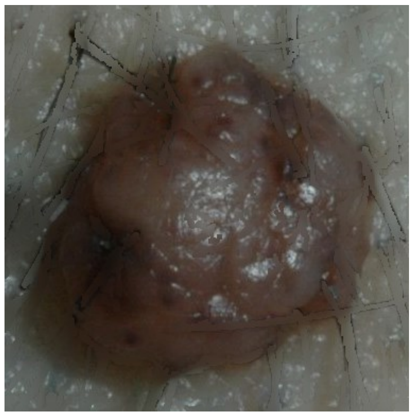
It then performs a morphological opening followed by a morphological closing on the layers to generate an open-close layer, and a closing followed by an opening to generate a close-open layer. These are then used to perform gap detection. If something is found in all layers, it will be treated as a possible hair. Then it will be checked for all branches where there are at least 2 other possible hair branches in the



(a) Image of lesion covered by thick dark hairs in a shade. Source: Huang et al. [5]



(b) Image of lesion covered by thick dark hairs in a shade after DullRazor® has been applied. Source: Huang et al. [5]



(c) Same source image as used in Figure 5b but now with proposed techniques from Huang et al. [5] applied. Source: Huang et al. [5]

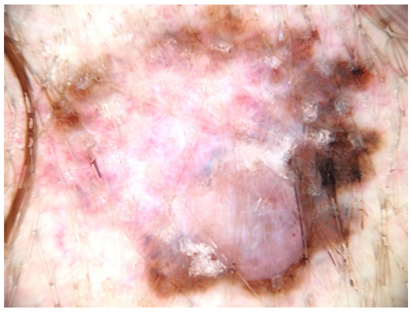
Fig. 5: Comparison of image with thick dark hairs removed by DullRazor® and Huang et al. [5]

neighborhood, if the distance between them is big enough to be separate hairs. This will thus produce a mask that shows where the hairs are located

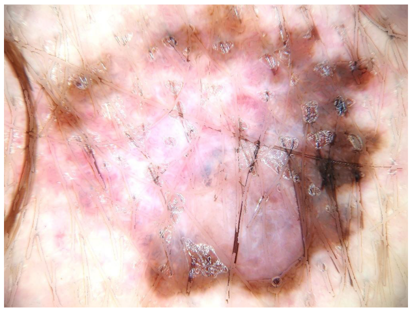
The hair replacement is done using inpainting using the fast marching method[9]. Because the reconstruction can happen using the mask on top of the original image, no smoothing is required.

A comparison of an image processed by Lee et al. [8], Huang et al. [5] and Koehoorn et al. [7] can be found in Figure 6.

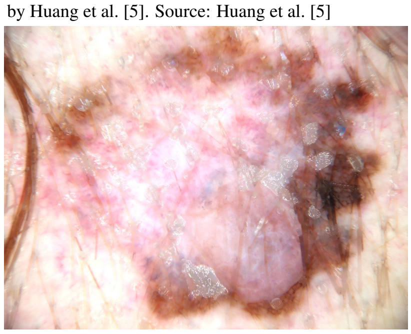
(a) Original image. Source: Huang et al. [5]



(b) Image after being processed by DullRazor®. Source: Huang et al. [5]



(c) Image after being processed by techniques described by Huang et al. [5]. Source: Huang et al. [5]



(d) Image after being processed by techniques described by Koehoorn et al. [7]. Source: Huang et al. [5]

Fig. 6: Comparison of image before and after processed by using various techniques

3 Results

In this section we take a look at the strengths and weaknesses of the algorithms and make a comparison between them. First we define the requirements for the comparison of the digital hair removal methods, then we will take a look at the methods with respect to the requirements followed by a summary.

3.1 Requirements

To perform the actual comparison between the digital hair removal methods we first need to define the important aspects for comparing these techniques. In general the following aspects are important;

1. quality of the hair detection
2. quality of the skin reconstruction
3. scope of situation which it works
4. ease of use, as in does it require a lot of configuration
5. performance, how long does it take to run

Since we do not have access to source codes or binaries of all the methods, it is not possible to go in depth on all these criteria. Therefore we define two requirements for our research, being accuracy as the combination of quality of hair detection and scope; and performance.

For accuracy we look into abilities of each algorithm. For example, DullRazor® is focused on removing thick dark hairs but runs into problems when it has to remove thin hairs or light hairs. It is important to know what each algorithm is capable off. We look at the ability of each method to remove hair in different scenarios. We take into consideration the following scenarios:

1. **Thick**, the ability of a method to remove thick dark hairs on a light background.
2. **Thin**, the ability of a method to remove thin dark hairs on a light background.
3. **Light**, the ability of a method to remove light hairs from a picture.
4. **Shadow**, the ability of a method to remove dark hairs on a dark background.
5. **Intersection**, the ability of a method to remove hairs when they are heavily intersected with each other.

3.2 A further look at the Methods

With the requirements in mind we take a look at the different digital hair removal techniques and give an overview of their strengths and weaknesses.

DullRazor® works well for thick dark hairs, as can be seen in Figure 1. However, it is quite bad at anything else. It does not handle shadow or lighter hairs very well because DullRazor® is partially based on contrast.

E-shaver improves on DullRazor® on a few key points. It can detect thin and light colored hairs, making it able to detect and remove more hair. The algorithm of E-shaver is a lot faster than DullRazor®, E-shaver is said to be 7 times faster[6]. However the algorithm experiences also some difficulties. It uses the absolute difference between gray values to detect hair; this means that hair can only be detected when there is enough difference between the color of the hair and the background.

VirtualShave is a relatively fast program with a focus on precision. The program has a measured 15.6% misclassified pixels, this is very low and about the same as a human test subject would have. For reference, they measured 47.1% misclassified pixels when using DullRazor®. This algorithm can only find hairs on high contrasted images. This is seen in Figure 3, where it has some problems finding dark hair on dark backgrounds.

Abbas et al. [1] proposed a technique focused on finding hair in low contrast regions. The accuracy of the method seems to be good as it has a measured mean hair detection error of 3.21% where they measured DullRazor® at 12.5%. In Figure 4 an application of the algorithm is shown where the hairs are removed on a dark background.

Huang et al. [5] improved DullRazor® to be able to handle lighter hairs, hair intersections and hairs that are in shadows and succeeded in this as can be seen from Figure 5. However, Huang et al. [5] noticed that the results of their technique were not optimal with hair intersections due to a high shape difference from a pure ridge structure and therefore also tested their technique using region growing and linear discriminant analysis based on pixel color information, it was able to remove hair intersections. All this improvement however came at a cost, as showed by Koehoorn et al. [7], as the technique developed by Huang et al. [5] is the slowest of all techniques discussed. Furthermore, Koehoorn et al. [7] also claims that their comparison shows that Huang et al. [5] blurs not only the hairs, but also the skin which would have a negative impact for further skin analysis.

Koehoorn et al. [7] describes a method that produces good results, as it claims to remove more hair than DullRazor® and Huang et al. [5], while maintaining an average speed in comparison with the other techniques.

3.3 Comparison of methods

The algorithms are rated on their ability to perform under the circumstances mentioned in subsection 3.1. In Table 1 there is an overview of the accuracy (as we defined at the start of subsection 3.1) of each algorithm, a plus means the algorithm is able of performing this task, minus means that the algorithm is unable to perform the task and an empty space means that there is not enough information for us to conclude if the algorithm is able to perform the task.

	Thick	**Thin**	**Light**	**Shadow**	**Intersect**
DullRazor®	+	-	-	-	
Huang et al.	+	+	+	+	+
E-shaver	+	+	+	-	
VirtualShave	+	+	+	+	
Koehoorn et al.	+	+	+	+	+
Abbas et al.	+	+	+	+	

Table 1: Comparison of accuracy of discussed DHR techniques

DullRazor® has a focus on removal of thick and dark hair and lacks in the other departments. E-shaver and Virtualshave improve on DullRazor® by adding the ability to remove thin hairs and light colored hairs but has problems with low contrast images and images with heavy intersections between hairs. Koehoorn et al. [7] and Huang et al. [5] can remove hair in all the scenarios.

In Table 2 there is an overview of the performance of the different methods. The table is based on the data presented by the respective papers and the overview that Koehoorn et al. presented.

Koehoorn et al. [7] found that Huang et al. and Abbas et al. [1] score the lowest on performance. In their test Huang et al. [5] did 10 minutes on an image and Abbas et al. [1] did 40 seconds while the rest of the methods are under 30 seconds. In this measurement DullRazor® comes out the fastest with 4 seconds, in this comparison E-shaver is not used, but in Kiani and Sharafat [6] it is stated that E-shaver is about seven times faster than DullRazor®.

	Speed
E-shaver	++
DullRazor®	+
VirtualShave	+
Koehoorn et al	+/-
Abbas et al	-
Huang et al	–

Table 2: Comparison of performance of discussed DHR techniques based on speed

4 Conclusion

In this paper we compared techniques described by Koehoorn et al. [7], Huang et al. [5], Abbas et al. [1], E-Shaver[6], VirtualShave[4] and DullRazor®[8]. All of the techniques use (a derivative of) the pipeline that DullRazor® introduced, but most specialize in one or more extra use cases that are not supported by DullRazor®.

If speed is the main requirement and intersections or shadows in the image are not a problem, E-shaver is the best choice. It mainly improved on the speed compared to DullRazor® and has the ability to remove thin and light hairs, while improving on speed.

If a better accuracy is necessary, one could look to the more heavyweight methods like Huang et al. [5] and Koehoorn et al. [7]. These methods have improved on accuracy while sacrificing on performance. The method described by Koehoorn et al. [7] can perform very well even with hairs in a low contrast situation or when heavily intersected and the method is a lot faster than the Huang et al. [5] algorithm. Koehoorn et al. should therefore be preferred.

If more performance is preferred but without sacrificing to much accuracy then Koehoorn et al. [7] is a good choice, VirtualShave is a good alternative that is about four times faster than Koehoorn et al. [7], while it can detect hair better in low contrast images than E-shaver.

For further research it would be interesting to actually implement the algorithms and test them on a big dataset to make a fair comparison based on data that we have direct access to rather than using second hand information.

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