Technical Report

Energy consumption and indoor air quality living labs

AsTeKa and TERTU

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1 Introduction

Increasing environmental awareness and high energy prices create demand for novel energy saving concepts. Therefore products and services such as monitoring of consumption habits and building of energy efficient houses have a growing market. The consumption choices of people are also increasingly made from a health conscious perspective. People spend a large part of their lives at home and thus a healthy living environment is very important. One key aspect in this is indoor air quality. Small particles and other pollutants in the air are linked to increased cancer and heart disease risks. Indoor air quality can be improved by having a well built house with good ventilation, but a monitoring system also offers benefits. It allows problem areas to be identified and fixed.

A system developed in the AsTeKa and TERTU projects at the University of Eastern Finland attempts to provide solutions to some of these issues. It allows companies and private end users to remotely monitor the air quality and energy efficiency of buildings. The system consists of a browser-based client tool, several web services for providing information to the client, and separate sensor networks for gathering and storing measurements from the buildings. The browser-based client acts as a customer interface to the system.

This report contains a documentation of the system and an analysis of its possible benefits when viewed from a smart grid perspective. Chapter 2 outlines the architecture and its key components. Then chapter 3 lists the types of measurements that are being gathered and presents the data sources that are currently attached to the system. Chapter 4 describes the browser-based client program. The emphasis of chapter 5 is on home automation systems, smart grids, and the benefits that can be gained by combining real time electricity consumption and pricing information with other measurements, such as ones related to indoor air quality. Chapter 6 has a summary and discussion on open research questions.

The funders and partners of AsTeKa were: Tekes/EAKR, Housing Fair Finland Co-op, FinnEnergia Oy, Kuopion Energia Oy, Ouman Oy, and Granlund Kuopio Oy. The duration of the project was from 2009 to 2010. The funders and partners of TERTU were: Euronom AB, Parha Oy, Saint Gobain Oy, FinnEnergia Oy, Air Wise Oy, Oy Nylund Group-Ab, and Housing Fair Finland Co-op. The duration of the project was from 2008 to 2010.

2 Overview of the monitoring system

The system is built in a modular way, making it extensible. It can roughly be divided into end user applications, data sources, a configuration server, and web services. The data sources contain various substructures, such as sensor networks installed into the houses, databases for storing the measurements, and data transmission devices and software. Most components of the system are accessible through web service interfaces.

Only a single end user application is currently available, a browser-based Silverlight monitoring client. Various indoor air quality measurements, energy consumption information, and weather data can be provided through the client. Depending on the access rights of a user, a single house or multiple buildings can be available for inspection.

Data sources are attached to the system with connectors; special dll files, which implement an abstract connector class. These adapters provide a standard interface for querying data in a unified manner, regardless of where the data comes from. A connector can be easily tailored to the specific needs of a data source, making the system flexible. Currently there are two data sources attached to the system, one related to AsTeKa project and another related to TERTU project.

The components of the system are distributed in different locations and communication between them is mainly done over the Internet. Within a data source, the gathered measurements are sent to a central server where they are stored in a database. Data can be collected at any resolution. For further information about data acquisition, see chapter 3. The measurements are accessible through a web service called DataService. It provides preprocessed time series data from all data sources connected to the system. The measurements are queried by specifying a time period, a location, a room, and possibly a channel id. An output resolution is also given. Thus the data can be averaged or summed to a desired precision. The connectors have a role of mapping the query to real sensors and to fetch the data. ClientConfigService and SignInService webservices, which are related to the Silverlight client and they are presented in chapter 4. Figure 1 illustrates the architecture of the system.

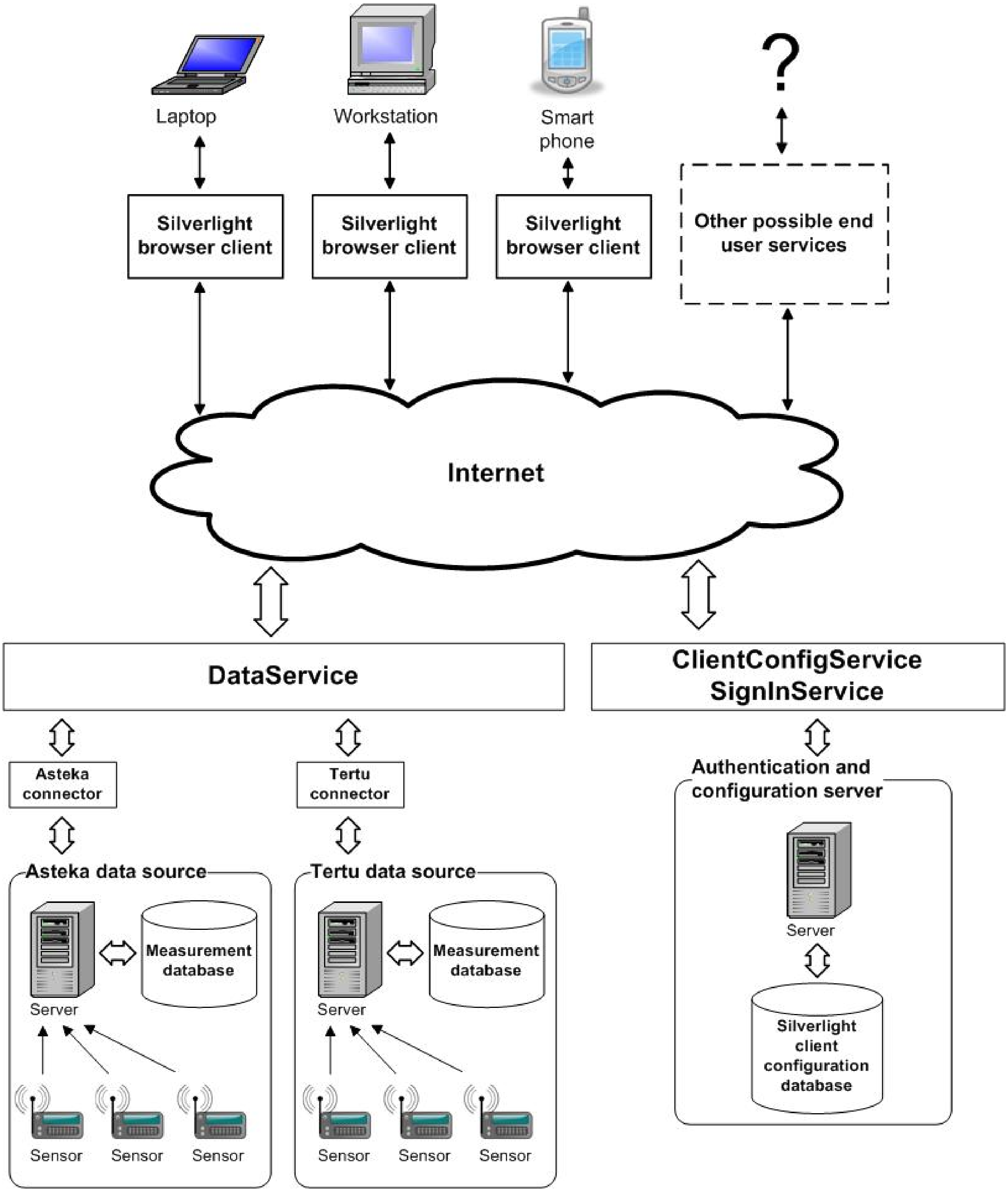


Figure 1. System architecture

3 Data sources

3.1 TERTU

In the TERTU project, several parameters are measured from a detached house. The structural behavior of the house is measured with several temperature and humidity sensors. These sensors are assembled between different layers of constructions of walls and base floor. Sensor electronics were developed by Savonia University of Applied Science (Information Technology) especially for the TERTU-project. The sensor networks are physically based on RS-485 field bus. The communication protocol in the bus is proprietary.

The indoor air quality of the house is monitored with respect to several parameters: temperature, humidity, CO_2, and particulate matter. The sensors are assembled in vented electricity assembly cases inside the ceiling. Sensors used are commercial standard 1-wire products.

The sensors are cabled as a bus topology using twisted pair cable for network installations (CAT5 / 6). Same cable is used to supply power for sensors as well as communication in the network.

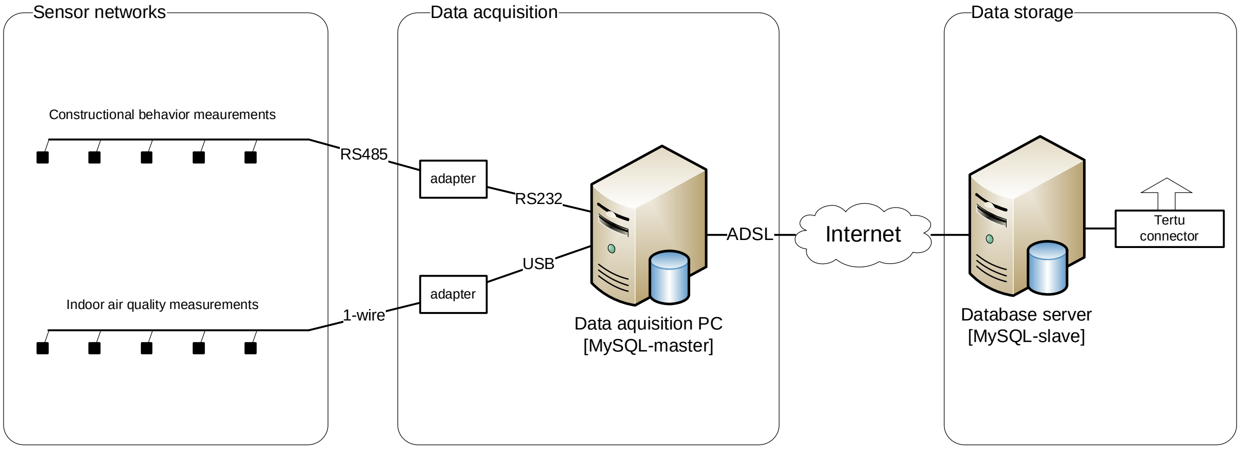


Figure 2. TERTU sensor networks and data acquisition

Data transfer can be divided into three parts as seen on the figure above. The sensor networks include sensors and cabling, which are assembled in the constructions of the building. Data acquisition is done in the same building at a separate measurement room. The endpoint of both sensor networks is also located in the same room. The measured data is transferred through internet to a database server at the University of Eastern Finland. The physical cablings of the sensor networks are fitted to a data acquisition pc with bus adapters (RS232 and USB). Data from the RS-based network is acquired with windows software made by Savonia. The software iterates all sensor addresses in the network and stores received data in text files. The text files are then transferred to a local MySQL-database.

Data acquisition from the 1-wire network is done with windows software LogTemp (http://www.mrsoft.fi). LogTemp connects to local MySQL-database directly and stores all acquired data.

Data is transferred through Internet using MySQL server's replication feature. In the replication setup, one server acts as a slave and another as a master. All modifications in the master server's database are replicated to a slave server. Replication is aware of breaks in the connection between the servers. When the connection is automatically established after the break, data transfer continues from the same point. ADSL-connection to the building is also used for maintenance purposes with Windows Remote Desktop.

The replicated MySQL –database is then used with TERTU Connector. This connector is a dll-component which is used as abstraction layer and connection point from the higher level system.

3.2 AsTeKa

In the AsTeKa project, various indoor environment and energy consumption measurements are gathered from 11 homes located at the housing fair area of Kuopio. The data is transmitted to a server for storage once every minute.

Indoor air quality is measured with respect to several parameters: relative humidiy, temperature, carbon dioxide, carbon monoxide, and pressure difference between inside and outside of the house. Water consumption, district heating consumption, and electricity consumption are also measured.

The measuring equipment consists of sensors, which are attached to a house unit called Asteka-box. Relative humidity, temperature, and carbon dioxide are measured with a single sensor from E+E Elektronik, which is located on a wall or the roof of a room. Water and electricity consumption are measured from the own consumption meters of the house to a

Kamstrup district heating meter. The house unit and its custom made software were developed at the University of Eastern Finland. It is based on a wlan-router, which has a Linux operating system. The house unit is connected to Internet either wirelessly via a 3G-connection or by Ethernet. For wired indoor environment sensors, the house unit has an analog I/O card. For analog inputs, we developed an adapter card, which converts the incoming 0V-10V voltage to a 0.0V-2.55V range. The server collects the measurements from the house unit and saves them to a database. Before the storage process, the voltage signal is converted to actual measurement units, for example 2V to 20 celsius for indoor temperature. The residents can view the measurements either throught the Silverlight client, which is described in the next chapter, or through Ounet product of Ouman Oy.

4 Customer interface

A Silverlight-based browser client functions as a customer interface to the system. It contains six different sections for normal users and special tools for administrators. The generally available sections are: a front page, a consumption page, an air quality page, a weather page, a living diary page, and a report page. A user can have rights to all of these pages or some subset of them.

When accessing the client, a username and a password need to be given. An alternative way to log in is to pass an encrypted token in the url, which contains an identification key and a timestamp. This is beneficial for third party software, which have a link to the Silverlight client. In these cases, the user has already logged in to the other software and there is no need to ask for credentials a second time. After logging in, a list of buildings is presented. The number of buildings available for inspection depends on the access privileges of the user. Alternatively, if a default building has been provided for the user, the program starts directly at the front page, which is illustrated in figure 3, or the first page that the user has access rights to.

Figure 3. Consumption meters

The front page has meters, which show the consumption of water, heating, and electricity for the most recent week and month. Each building has a set of load profiles associated with it, which give the expected consumption for normal circumstances. The readings of the front page meters are obtained by comparing the measured consumption to predictions given by the profiles. The load profiles are calculated from historical water, electricity, and heating consumption measurements of the building or from consumption data of similar buildings. The profiles are constructed by fitting weighted multiples of sine and cosine curves to historical consumption time series data. If outdoor temperature measurements are available, it is also possible to calculate temperature correction coefficients for the consumption variables. These coefficients can be used to remove the influence of outside temperature from the time series. For example, if a house is electrically heated, electricity consumption is highly dependent on outside temperature. To have a reliable comparison between current consumption and the profile, it is necessary to apply temperature correction.

It is also possible to query for more detailed consumption time series data. To inspect data from a desired time period, the user of the client selects one or multiple sensors and the length of the shown time window. Then it is possible to browse back and forth in time or directly choose an ending date for the time window from a calendar.

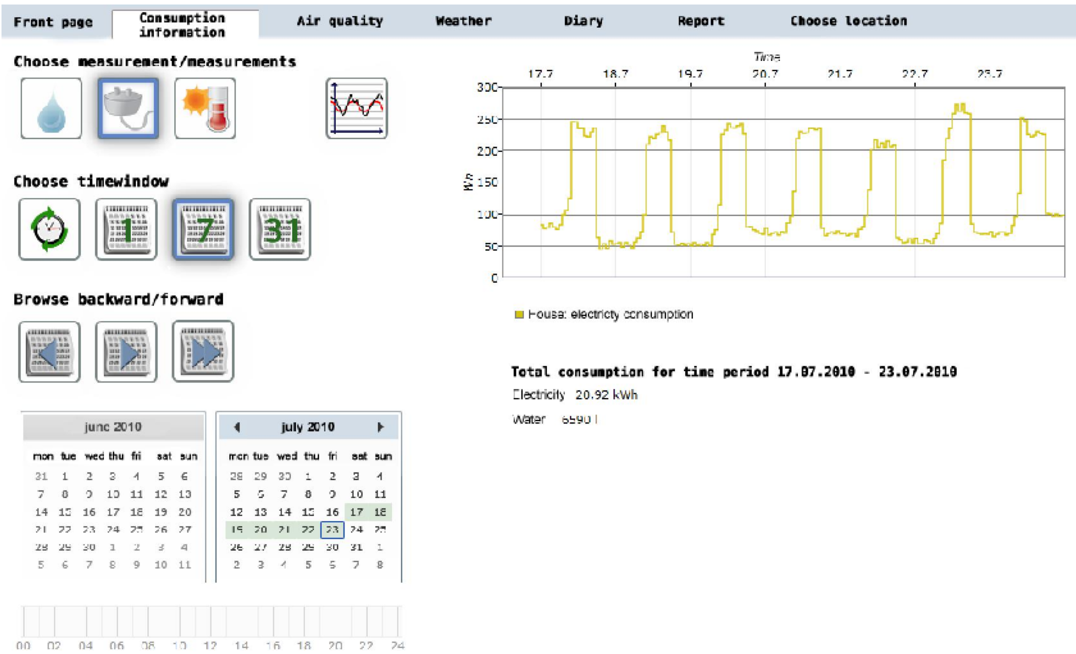


Figure 4. Consumption time series data

Indoor air quality information is accessible through its own section. A time window can be selected in a similar way as with the consumption data. Various time window sizes are available: a month, a week, a day, and a tiny window. The user can specify the size of the tiny window to a range of desired hours within a day. When data is retrieved from the server, it is averaged or summed to a suitable resolution for the time window. This makes interpreting and visualizing the results easier. For most types of indoor measurements, it is also necessary to select one or more rooms from a floorplan. Figure 5 has a screenshot of the air quality section. In the picture, living room temperature and humidity sensors have been selected and a monthly time windows is used.

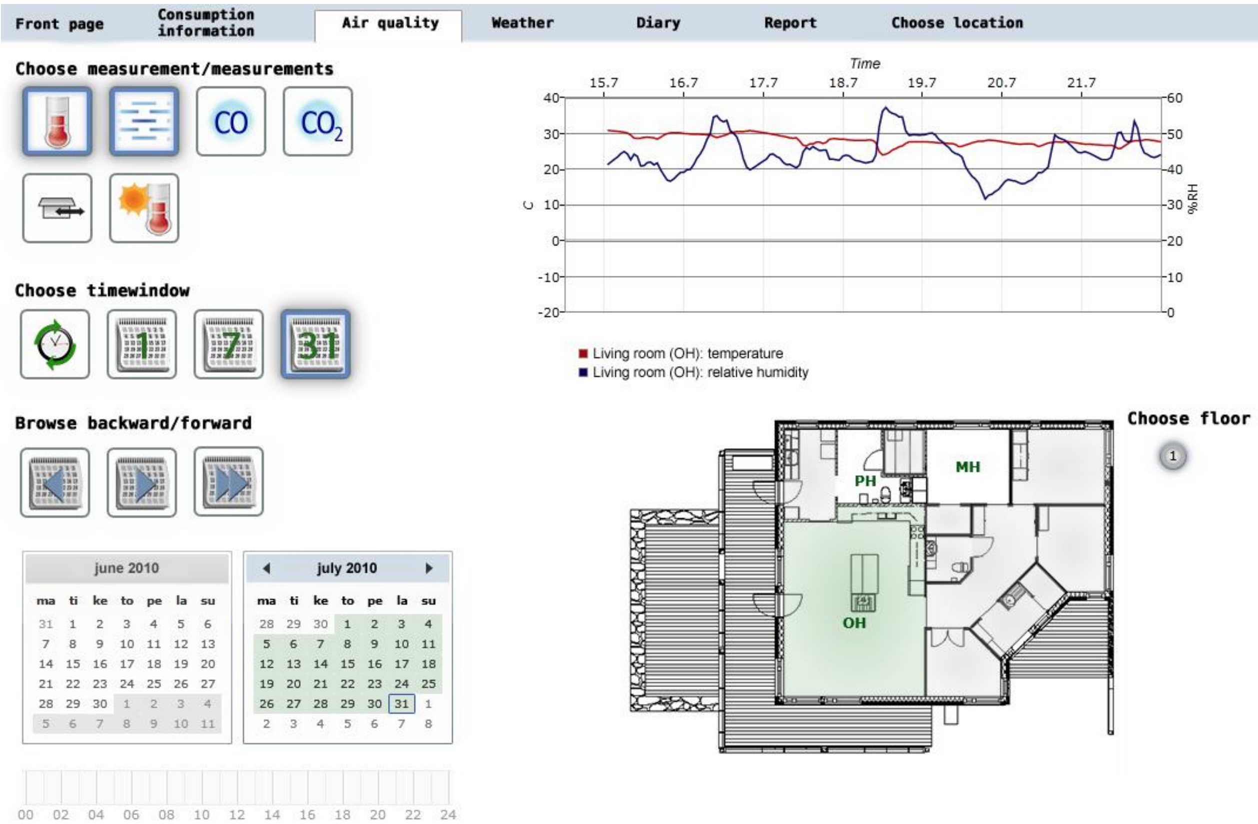


Figure 5. Indoor air quality

Weather information is also provided. Rain count, outdoor temperature, wind direction, and wind speed can be inspected in the same manner as consumption and air quality time series data. Figure 6 illustrates the weather section.

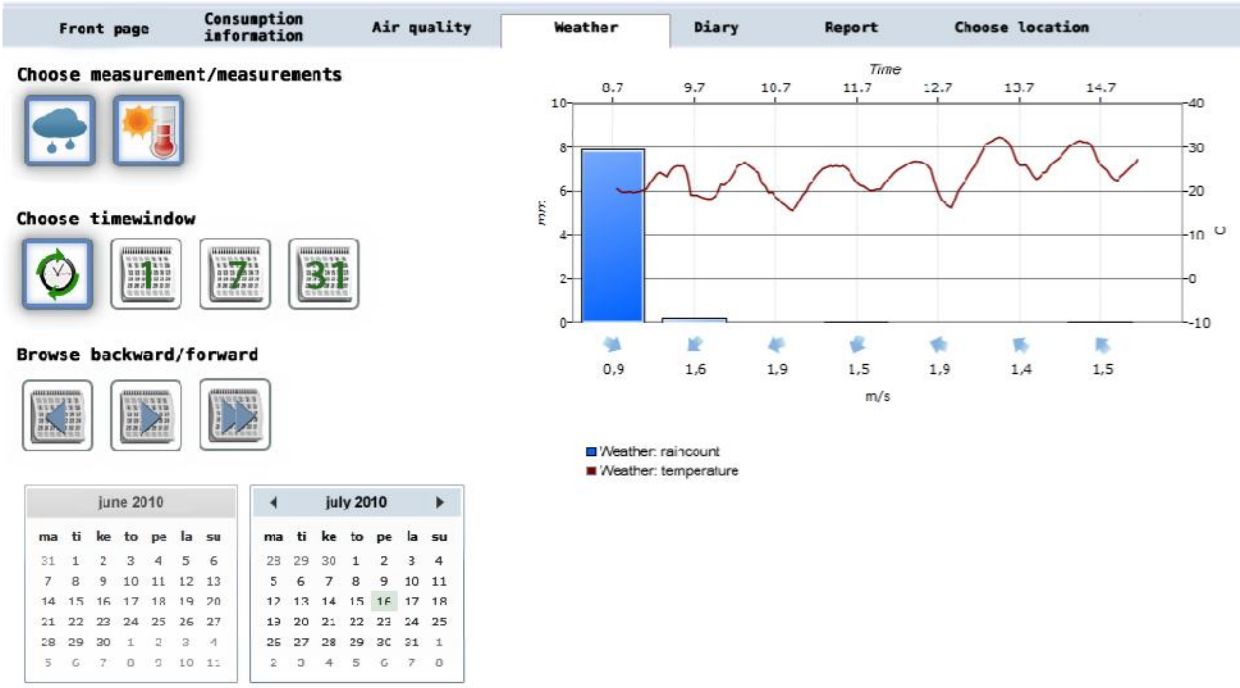


Figure 6. Weather information

The program can also generate pdf reports from consumption and air quality measurements. The reports contain monthly consumption totals and average bedroom air quality for a few path months. Figure 7 has a screenshot of the report tool.

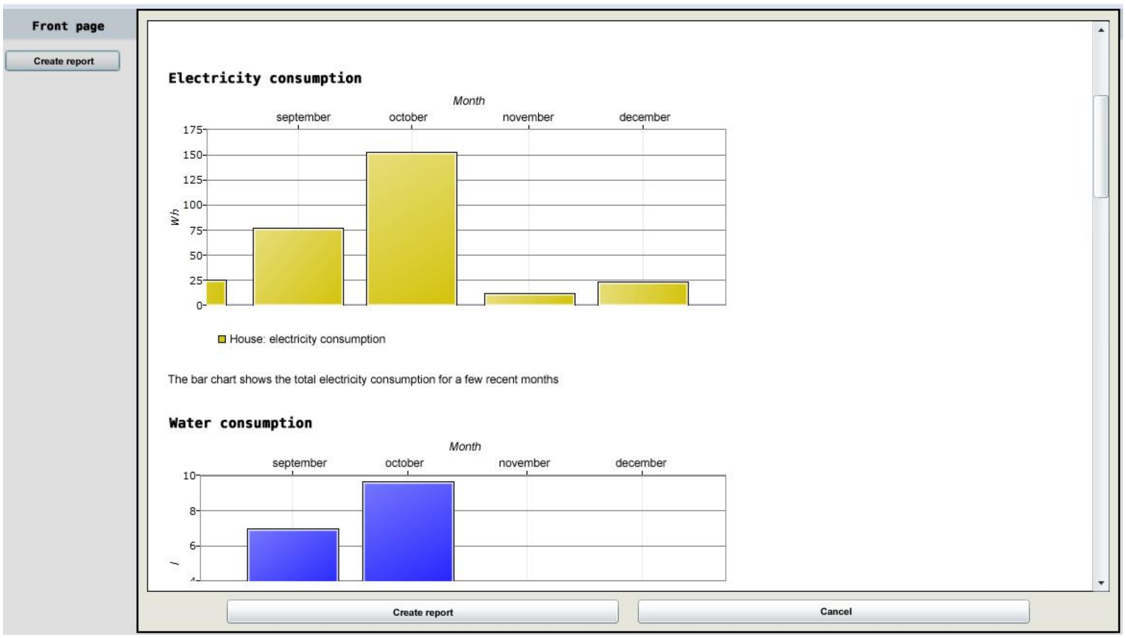


Figure 7. Reports

The Silverlight client gathers living information from private home owners who participate in TERTU and AsTeKa projects. The residents keep a diary, where they report various events, which could affect air quality. This information is used later for research purposes. Figure 8 has a screenshot of the diary.

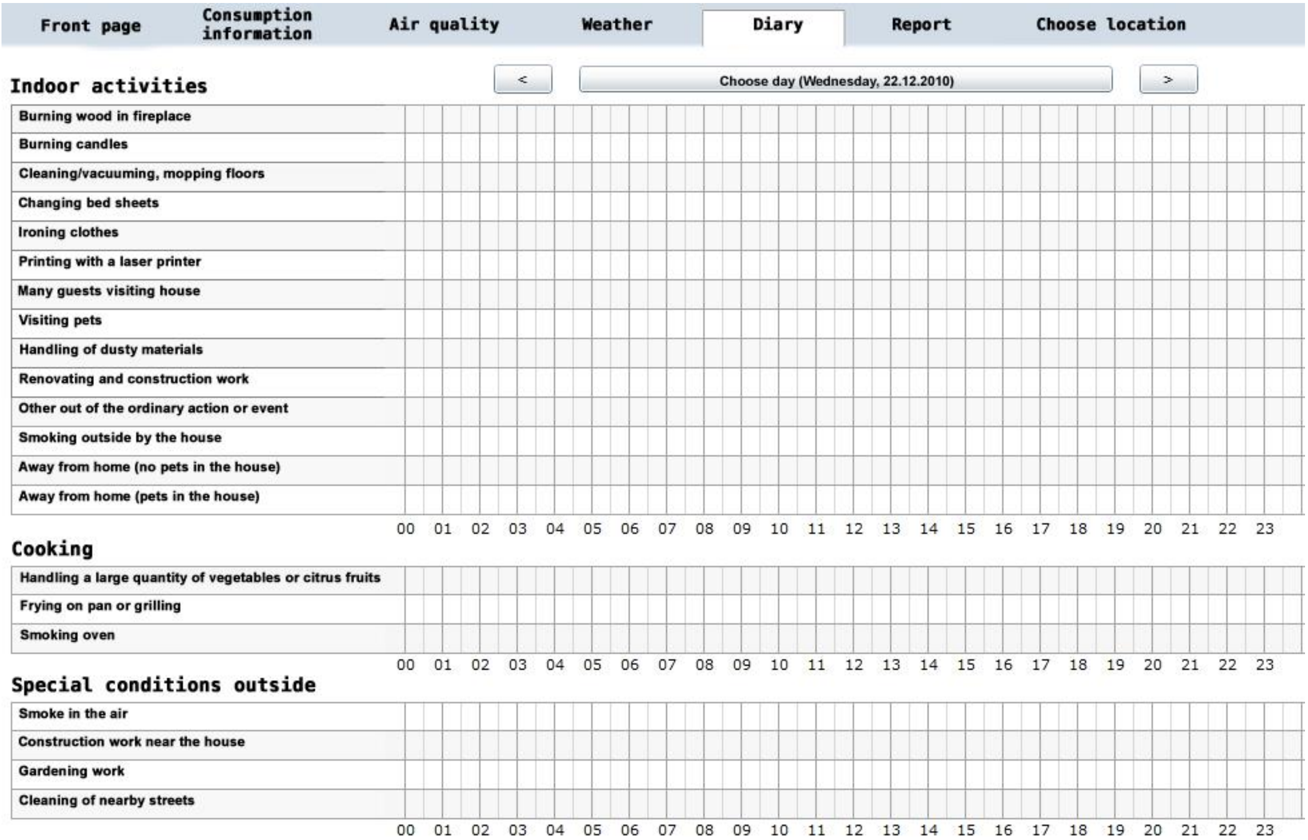


Figure 8. Diary

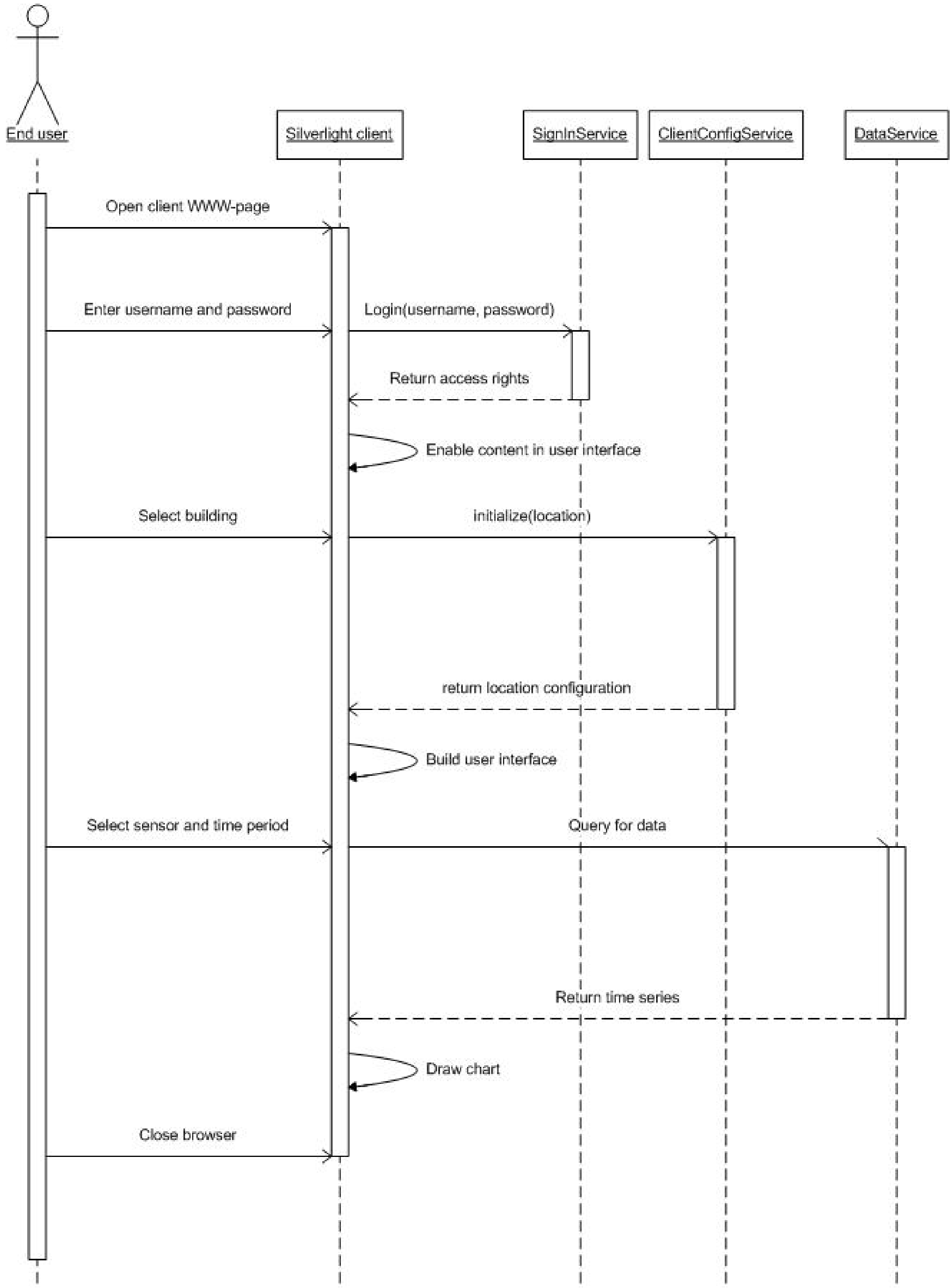


Figure 9. Silverlight client functionality

Figure 9 illustrates the workings of the Silverlight client. The browser client makes queries to web services to authenticate the user, to download location specific sensor information, and to fetch time series data.

An authorization web service called SignInService controls access rights for users to the client. The service determines which buildings can be inspected and what content is available in the client. Once a building has been selected for viewing, a call is made to a configuration web service called ClientConfigService. The service returns a list of rooms in the building, possibly a floor plan, and a list of sensors associated with each room. Information is also provided how data should be visualized for the given sensors. Then the user interface of the client is built dynamically according to the results returned by these web services calls. When using the client, measurement time series data is provided through DataService. SignInService and ClientConfigService are tied to the Silverlight client, but DataService can also provide data for other applications. Thus it is possible to build new software and services, which use the same data as the Silverlight client. The next chapter has a description of how DataService could be used as a part of a home automation system.

5 Link to home automation systems and smart grids

The measurements gathered in TERTU and AsTeKa projects could also be used as inputs for a home automation system. Figure 10 has an illustration of this.

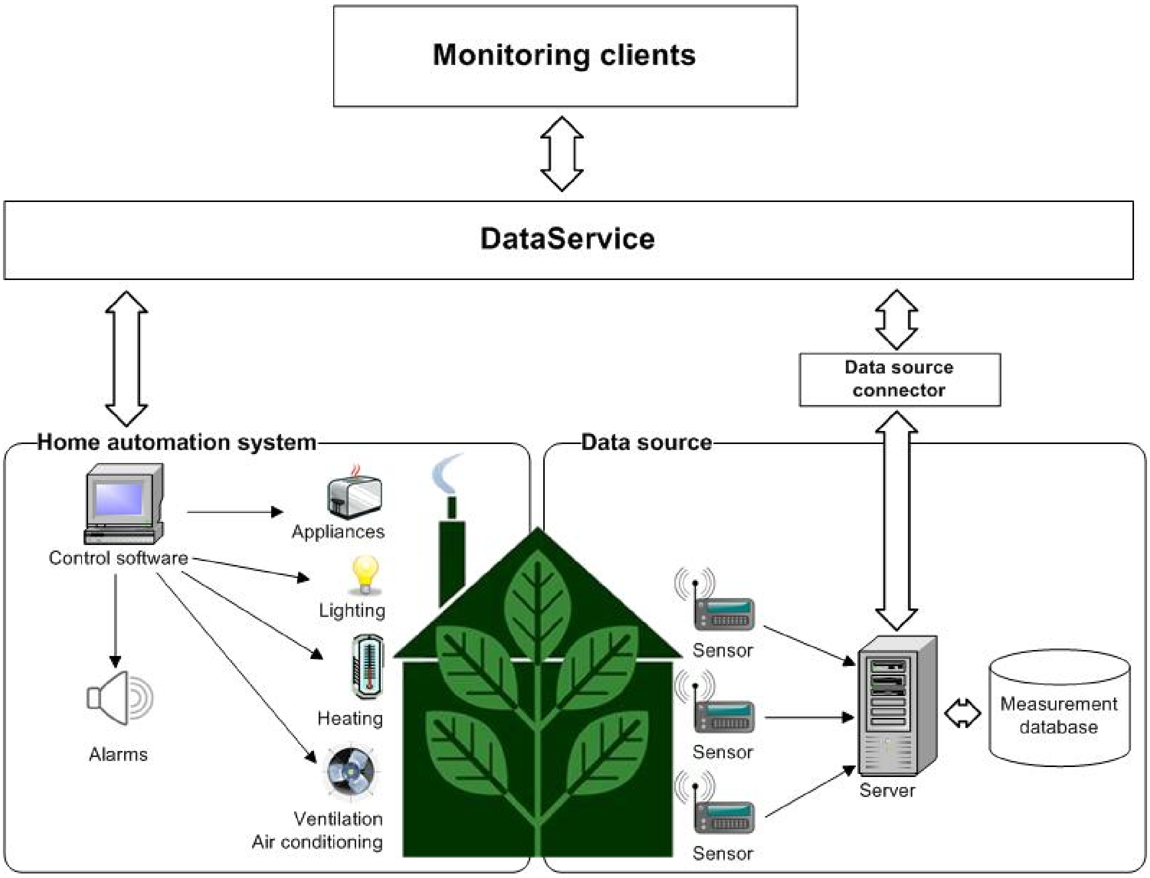


Figure 10. AsTeKa as a part of a home automation system

Home automation systems, also called domotics, automatically control the workings of home appliances, lighting, ventilation, and air conditioning. As a result, living becomes more ecological and comfortable. Adjusting heating according to indoor temperature can also give considerable savings in utility bills. Home automation systems can improve the safety and security of living by sending alarms in abnormal situations. For example, an SMS message could be sent to a mobile device when measurements fall outside of accepted ranges. Then the receiver of the message could send back a response to remotely control some device and solve the problem. The final development step in home automation systems could be an intelligent home, which learns to anticipate the behavior of the residents and to adjust its domotics accordingly.

5.1 Smart grid networks

Current electricity networks face multiple challenges. Global electricity demand is rising and the rate of increase is likely to accelerate as the developing countries in Asia improve their living standard (Lior, 2010). The introduction and adaptation of plug-in vehicles is also likely to have a dramatic impact on circuit loading (Ipakchi and Farrokh 2009). At the same time, greater reliability is required. However, old electrical grids are vulnerable to problems and an isolated event can lead to a cascade, which quickly causes the entire network to malfunction. The infrastructures of a modern society are higly interdependent and the potential ramifications of grid failures are far reaching. (Amin and Wollenberg 2005)

Another major concern in energy production is growing carbon dioxide emissions and other environmental factors (Solomon et al., 2009). The industry has to balance between resource adequacy, reliability, economics, environmental constraints, and other public purpose objectives. Transmission and distribution resources have to be optimized to meet the needs of the end users. (King, 2008)

The industry is facing changes, which require large investments. This transition into new types of electricity networks, smart grids, will offer economic advantages for both utility companies and electricity consumers. Smart grids will also promote environmental sustainability and open up possibilities for new types of services. A smart grid extends an ordinary electricity delivery network with intelligent software and hardware. It should provide new functionality, such as self-healing, higher reliability and power quality, real time pricing, and resiliency against malicious cyber attacks. It is likely to have lower operations and maintenance expenses and it will optimize asset utilization. From a design perspective, a smart grid will incorporate new technologies such as advanced metering, automation, communication, distributed generation, and distributed storage. (Brown, 2008).

Utility companies have to be prepared for fluctuations in electricity consumption. Reducing peaks in these fluctuations could produce significant savings and improve the reliability of the grid (LeMay et al., 2008). Various methods for load management have been around from the early 1980s. They include direct load control, peak curtailment, peak shifting, and voluntary load management programs. With intelligent end user electrical devices, decentralized generation, smart metering, and realtime pricing, demand response techniques can be implemented more efficiently. As smart electrical devices have online pricing information available, their use can be timed to maximize economic benefit. With smart grids, the system operator will be able to monitor and manage demand either directly or through price signals. The grid will be ready to move from a load following strategy to a load-shaping strategy, in which demand-side resources are managed to meet the grid's available capabilities at any time. (Ipakchi and Farrokh 2009)

Demand response methods have been explored extensively in the literature. We take a novel perspective by augmenting electricity consumption and pricing information with indoor air quality and weather measurements. Thus economical benefits are not the only incentive for a customer, but the objective is to find an optimal balance between comfort and costs, while maintaining a healthy and safe living environment. Current results from AsTeKa and TERTU projects do not offer a convinient way to achieve this goal. The gathered measurements only work as supporting knowledge for consumption decisions. In the ideal situation, the home automation system would not need to be adjusted and it would learn its optimal settings by following resident behavior.

5.2 A vision of an adaptive house

LeMay et al. give an imaginary example of a microwave oven that could read a bar code from a food package and fetch cooking instructions from the Internet (LeMay et al., 2008). Similar intelligence could also be built into other aspects of home automation systems. Ventilation, heating, and air conditioning could be tuned by electricity price, measured air quality, indoor temperature, and inhabitant preferences.

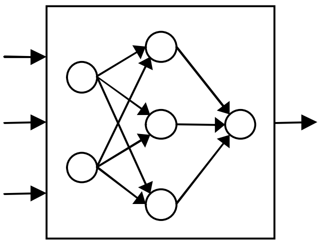
Various smart homes have been presented in the literature. P. Rashidi and D. J. Cook (Rashidi and Cook 2009) apply machine learning and data-mining techniques to a smart-home environment in order to detect resident activity patterns, generate automation policies for those patterns, and also adapt to the changes in those patterns. M. Mozer describes a system (Mozer 1998), which uses intelligent computation methods to learn about resident preferences and to optimize energy consumption. The smart home presented in (Mozer 1998) has been implemented in a real residence. We next describe an idea of an adaptive house, which gives tools for managing customer side demand response while improving indoor air quality. Our concept is still just a vision and more research is needed if it is to be implemented.

5.2.1 Comfort profiles and indoor environment prediction models

The preparation of the house can be split into two phases. In the first phase, models are built for forecasting indoor living environment conditions and the house learns about resident preferences. Several models are necessary for making predictions in different horizons. For example, indoor temperature prediction models could be trained separately for each room in the following way: one for predicting the temperature after 30 minutes, another after an hour, and a third one after two hours. It might be possible to make even longer predictions if weather forecasts are available to be used as model inputs. These prediction tasks are very difficult. The phenomena to be modeled are influenced by multiple variables and dependencies between model inputs and outputs are likely to be nonlinear. Since historical and current measurement data is available from the sensors, we propose to use neural networks to implement the models. Figure 11 illustrates a temperature prediction model. Note that other models, such as carbon dioxide and humidity models, would have a different set of inputs and outputs.

Inputs:

- Indoor temperatures
- Time and day
- Outdoor temperature
- Current level of heating
- Current level of air con.
- Weather forecast?



Output:

- Predicted temperature after 30 minutes

Figure 11. Temperature prediction model

The models take as inputs current home automation settings, such as the level of heating and air conditioning. Thus when changes are made to these settings, it is possible to predict how it reflects in the indoor environment parameters in the near future.

Once the adaptive house is operational, it keeps track of every action made by the inhabitants. This information is used for forming baseline comfort settings. For example, the user might set different temperatures for different rooms from the thermostat. This action is recorded and it influences the comfort profiles. Some air quality measurements might be difficult for the user to interpret. For example, a resident might not know what is an optimal carbon dioxide level. Thus it is a good idea to also provide default ranges for all settings. The comfort profiles can be time dependent and they might allow a wider range of variation in some situations. For example, as an initial default setting, it might be reasonable to allow indoor temperatures to vary within a larger range when sensors show that the residents are not at home. The comfort profiles could be implemented as simple time series, or as neural network models. More research is needed to determine the ideal solution. Comparing current measurements and predictions to the profiles gives comfort cost functions $C_k(n)$, which tell how far a given situation is from the ideal zone. The subscript k in the cost function determines which comfort profile is used and n is a measurement or a prediction.

In the second phase, the comfort cost functions are used to guide the home automation system. Electricity consumption is also optimized in a manner, which attempts to keep indoor environment parameters as close to user preferences as possible. If economic advantage can be gained and negative implications are minimal, consumption events will be postponed or made earlier. The system should also have tunable parameters, which determine the balance between economical aspects and inhabitant preferences. If an economy parameter is specified for every device that is connected to the adaptive house, the resident can prioritize certain preferences over others. For example, it might be more important to have good air quality than pleasant indoor temperature.

5.2.2 Electricity consumption optimization

In our approach, it is assumed that electricity prices are known for some time into the future or reliable short-term forecasts are available. Let the prices be given by function E(t), where t denotes time. The goal is to optimize consumption decisions in a time window, which extends a couple of hours into the future. To perform the optimization, it is necessary to calculate expected total comfort and electricity costs in the time window. With this information, it is possible to search for the optimal set of predictive control actions. Recall that for every possible control action, its comfort impact can be predicted by feeding the new settings into an indoor environment prediction model and comparing the result to a comfort profile. If the amount of electricity consumed by an action can be estimated, it is possible to form a search space, which consists of 3-tuples (action, comfort cost, electricity cost). Now the optimal solutions form a Pareto surface and the economy parameter determines which action or actions are selected from the surface. Note that an action can also be “do nothing”. Figure 12 illustrates the optimization problem. The gray area contains the search space and the blue curve denotes the Pareto surface.

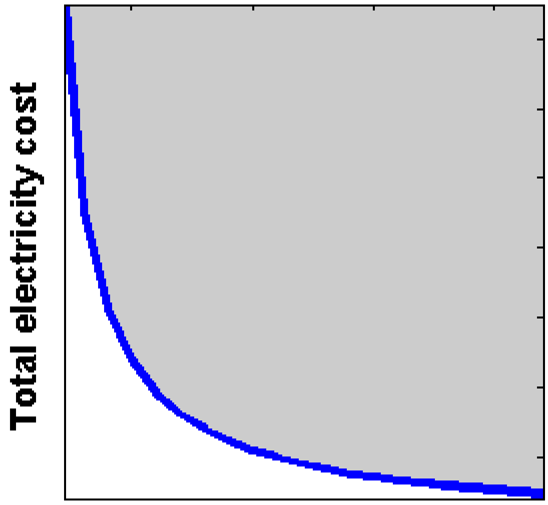


Figure 12. Control action search space

Table 1 lists example control actions and the costs associated with them. These actions could be, for example, to adjust the level of air conditioning, heating, and ventilation.

Predictive control action	Total comfort cost	Total electricity cost
Air con. action 1	5	0,1
Heating action 1	2	0,9
Heating action 2	1	1,3

Table1. Predictive control actions

The home automation settings should be optimized frequently to obtain the best possible results. The search space is very large and it is computationally intensive to evaluate the goodness of a control action. Therefore a heuristic is needed for cropping out actions, which are guaranteed to be bad. It is also necessary to define limits where the measurements are allowed to vary. No control action should be considered, which would push a parameter out of the allowed bounds. If a measurement goes out of its accepted range, home automation settings should be adjusted regardless of the cost functions.

If reliable future electricity pricing information is not available, the optimization problem becomes more difficult. Now it is not possible to evaluate the electricity cost of postponed actions. We suggest that the search space is then restricted to actions, which can be initiated immediately. The electricity cost function should be based on current price information and the optimization should be done very frequently to be prepared for changing conditions.

6 Discussion and summary

This report describes the monitoring system developed in the AsTeKa and TERTU projects at the University of Eastern Finland. An overview was first given in chapter 2. Next, two measurement data sources were presented. Chapter 4 continued by describing the end user customer interface. Chapter 5 analyzed how the results of the projects could be integrated into a home automation system. Smart grids and an adaptive house were also discussed in chapter 5. As a conclusion, the gathered air quality measurements could be valuable inputs for an intelligent home automation system.

The adaptive house concept was presented on an abstract level and more research is still needed if the system is to be implemented. Viewing the possible benefits from a demand response perspective, it is unclear how efficient peak leveling could be achieved and how it would translate into economic benefits.

Another open question is which indoor air quality parameters would be suitable for the system. Temperatures are likely to be predictable, but CO_2 and particulate matter levels might pose problems. For example, carbon dioxide is influenced by random events, such as guests staying at the house and opened windows.

When implementing the adaptive house, it should be taken into account that a control action, which is optimal in one sense, might have a negative impact on some other air quality parameter. For example, increased ventilation might result in heat loss.

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