BUILDING MONITOR

DEVELOPMENT OF A MONITORINGSYSTEM FOR BUILDING EFFICIENCY & INDOOR CLIMATE

Report Research Project ‘MP-BEIC – ‘BUILDING MONITOR’’

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INTRODUCTION

Gilb's Law:
"Anything you need to quantify can be measured in some way that is superior to not measuring it at all." [1]

1 Aims and Topics

1.1 Interaction of people and buildings

The project 'Building Monitor' developed a system for the monitoring objective (physical) and subjective (psycho-sociological) information about user comfort, indoor climate and energy performance of buildings. In this way we evaluate and optimize the building performance of the houses. This monitoring opens up new possibilities to reduce CO_2-emmissions and to improve the Well-Being of the inhabitants. Therefor, new tools and methods were developed to describe the indoor climate and energy performance of buildings and optimize the interaction of the people living in it. With the system three data sources were combined and compared:

Planning:	Calculated values (simulation data and energy calculations)
Technical Monitoring:	Measurement of physical values
Social Monitoring:	Feedback and survey of users

At the beginning of the research it was assumed that the indoor climate and well-being of the user can be reduced to a unified model valid for all users. This assumptions has prove to be wrong and caused a shift of the research away from a unified model to identifying individual preferences of users and the modification of the indoor climate model according to subjective criteria.

1.2 Well-Being

Building research has focused in recent years on optimizing the building according to the technical aspects. In this respect the indoor climate in buildings has been improved

[1] The original quote by Tom Gilb in Gilb's Law: "Performance requirements must express quantitatively the stakeholders' requirements. I have come to believe, through experience, that all the performance attributes we want to control in real systems are capable of being expressed measurably. I find it intolerable that critical performance ideas are expressed in mere non-quantified words. Expressions like "vastly increased productivity" annoy me! Not Performance attributes are more than a collection of names like 'reliability', 'user friendliness', 'innovation', 'transaction time' and 'cost saving'. Each performance attribute needs to be precisely defined by a set of numeric, measurable, testable specifications. Each performance attribute specification will include different specified levels for different conditions [time, place and event]. Unless there is clear communication in terms of numeric requirements, there is every chance of the real requirements not being met; and we have no clear indication of the criteria for success and failure.
Sometimes, it seems difficult to identify satisfactory scales of measure. Often, the only ones that can be found are indirect, imprecise, and have other problems associated with them. From my point of view, these problems can be tolerated. The specific scales of measure, and meters for measuring, can always be worked on …"

dramatically. The effect of buildings on humans is not as well studied. In the ‚Well-Being'-research[2], which underlies the development of ‚'Building Monitor'' project methods are implemented, by which the effect of the building on their inhabitants are monitored and evaluated.

The aim of 'Building Monitor' was to develop a model for the collection, analysis and systematic evaluation of the experiences of users in buildings. The results of sociological research, which was part of the project, into the interaction of users, their behavior and the building suggests, that it will be most successful when it is as specific as possible and relating to real time situation. The user needs to see and understand what the building is doing right now in order to modify his performance to the end of a reduced energy consumption and improve the Well-Being.
An important aspect of the user and well-being research is as a novelty that the 'Building Monitor' seeks to modify the behavior of users and to gear them into doing so by increasing their housing wellbeing. So the key element of the 'Building Monitor' is that it interacts with the user aiming at the enhancement of housing wellbeing. The project's primary aim is not just to display information about the house, but to get the user to act and modify her or his consumption habits. Development of a low-investment and highly responsive monitoring device.[3]

1.3 A low investment Monitoring Tool and User Interface

One of the most important aspects of the research is a low-investment and highly responsive monitoring device that brings together all aspects of the interaction between users and buildings:[4]

- Well-Being users (detected by a survey and subjective evaluation)
- User information
- objective measurement of indoor climate
- energy performance of the building

To lower the costs the modelling of 'Building Monitor' is based on a minimum of hardware, extrapolations and data, which can be gathered from the simulation data of the planning stage. During a short installation process 'Building Monitor' gathers this information by means of a structured interview with the home owner and/or occupants of the building. The more specific the information of the inputs are the better the accuracy of the model. But even with very little information (year of construction, size of the building, number of occupants) it should be possible to assume the energy use of the building within a range of 20% by comparison with similar building typologies.

Based on the idea that even with a small number of measurement points and using already available consumption data, a relatively accurate description of energy production, energy consumption and the distribution of energy consumption of the

[2] Wegener, B. & M. Fedkenheuer 2014
[3] Wegener, B. & M. Fedkenheuer 2016
[4] Golla, B. 2015

building can be made. The data is collected by an operator or inhabitants of buildings and entered in a specially developed interface or app and internally evaluated. To ease the collection of the data an app for computers and tablets will be developed which reminds the user to input the data and make the input quick and comfortable.

The active measurement and additional hardware necessary is limited to the installation of a ‚NetAtmo‘ device, which collects data about the indoor climate (temperature, humidity) and the weather. Given this information about the season, real time information about the weather and the time of date, it is possible to extrapolate which aspect of the energy use (heating, hot water, lighting, appliances…) is predominant at a specific interval of time.

‘Building Monitor’ includes a semi-manual monitoring, which also includes the manual input of data. For example the energy consumption, for which a real time extrapolation is achieved based on the given measurements of indoor climate and weather, can be validated by the actual energy use of the building. This information, which is displayed on the meter, the user can input and thereby improve the quality of the data in the model of ‚’Building Monitor’‘. The system is capable of re-evaluating and adjust the extrapolations according to the real energy consumption. This also gives a better benchmark for future extrapolation. In theory it would be possible to design a learning system, which improves future predictions by comparison of the current model and the measured data. This feature was not realized in this stage of the project.

1.4 User information and interaction

The social research conducted in the ‘Building Monitor’ project suggests that the success of an information system to reduce energy consumption and improve the Well-Being depends on the capacity of the system to react very specific to:

- Each individual user (preference and behavior)
- Each situation (weather, specific energy profile at a given time interval) and the possibility to display the information as dynamic (real time) and active as possible.

These assumptions contradict the initial concept of ‘Building Monitor’ as a very simple and affordable system. The more detailed, individual and dynamic the information modelled and displayed by the system gets, the more complicated and expensive the technology is, that might be able to provide it.

2 Expectations

2.1 Technical Expectations: Prototype device

The expectation for the pathfinder project was to build a prototypical device or system that would serve as a model for the prototype. This system should have included hardware and software components, which could be installed in an actual building as a first application case.

The research into the social aspects of the well-being indicated that such a device might fall short of the expectations for the whole project. Based on available hardware, model and methods the prototype could only display information about the indoor climate and the building performance in a conventional way. Static one-directional information about building performance and indoor climate does not change the user's behaviour consistently nor does it accurately describe the subjective perception of well-being (also see chapter 6).

The new sociological model for the well-being development in this research indicated a much more effective way to monitor well-being and to influence the interaction of the building and the user. It might not be necessary to overload the users with unspecific information about the behaviour of the building if only certain information would be useful.

2.2 Scientific Expectations: Computational model and description of Well-Being

The central component of the prototype is a computational model, which allows to display, compare and evaluate the measured data gathered from the hardware devices. The concept for this modelling was, that a larger array of typical buildings were identified in terms of there characteristics, which in terms allows for a mapping of data for the these typical building's performances onto the computational model of 'Building Monitor'. This modelling gives a close enough simulation of what the building is doing under certain climatic and other circumstances. However, the classification of the typical buildings proofed to be complicated, since many factors influence the energy consumption (A/V ration, building envelope, building equipment…). The main disadvantage of this computational model would have been, that it is not responsive. Since the data is only passively mapped onto the building without relation to the actual operation and current situation, the data resulting from the mapping would not change when the inhabitants changes the control of the building: for example, turning down the heat would not lower the displayed heat energy consumption. Since responsiveness was identified as one of the most important incentives for behavioural change, the concept of a non-responsive computational model was dropped. Instead a modell was implemented, which is based on the actual measurements of the indoor climate and therefor more responsive in real time.

2.3 Product Expectations

The expectation towards 'Building Monitor' as a product are described in section 14. Still a very important incentive for the project partners was the idea to develop a simple device for monitoring buildings. The system should be appealing to the users in the way its ease of use as technical features. Creating a low-price 'Building Monitor' would open up the possibilities of better understanding and controlling building to home owners and tenants.

METHODOLOGY

3 The computational model and display of information in 'Building Monitor'

3.1 Prioritizing information

The challenge of 'Building Monitor' is to achieve a display of the performance and energy use of the building which is comparatively accurate and as real time as possible.

The results of our sociological research into the interaction of users, their behavior and the building suggests that it will be most successful when it is as specific as possible and relating to real time situation. The user needs to see and understand what the building is doing right now in order to modify his performance to the end of a reduced energy consumption.

This would be easy to do if on the hardware side 'Building Monitor' were to include many metering points which collect real time data about the energy use in different dimensions (heat, electricity…). Though this would be the most effective way to get an accurate and transparent image of the building's real time energy use it would be to expensive to install all the equipment necessary to get accurate real time data for all dimensions. The difficulties involved and possible approximations will be discussed in the following sections.

The general aim of 'Building Monitor' is to prioritize the information displayed to the user according to

- The importance of the information in reference to the overall energy use at any given time interval
- The importance of the information in respect to the overall energy use of the building over an entire year
- The possibility to optimize the energy use associated with a specific information

It does not help to reduce energy use and Carbon emissions if the information displayed represents only a small fraction of the actual energy use of the building. 'Building Monitor' must understand the entire energy use and refer specific values to the overall picture. A certain threshold should be defined (i.e. 10%) under which the information will be suppressed by the system as being negligible.

The concept of 'Building Monitor's' approach is based in the Pareto Principle, which states that in many natural and androgenic systems 80% of the success can be achieved from only 20% of the effort. It is usually the last 20% of perfection that account 80% of the effort.

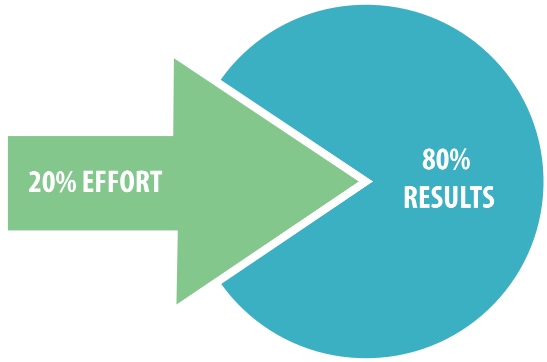

figure 1 The Pareto principle

This applies especially if it comes to simulations or measurements. If a certain amount of inaccuracy is acceptable a model can be build based on little data and comparatively rough assumptions. For ‘Building Monitor’ it is not important to achieve a very high level of accuracy in the simulation or display the performance and energy use in the building. The important part is to get the magnitude of the consumption right enough for the user to make an informed decision for his actions.

An accurate and instantaneously measurement of the building would require hardware and software that would probably raise the price range of ‘Building Monitor’ even with high production numbers to more that 5.000,00 Euro for a single family house. This would translate into a demand only for a small minority of highly motivated users. Since ‘Building Monitor’ aims at a very broad market the costs should be much lower. To lower the costs the modelling of ‘Building Monitor’ must be based on very little hardware, extrapolations, and statistical data, from which the best matching set of data for a certain application case will be picked. This process requires the system to gather information about the classification of the building, its occupants and their behavior. During a short installation process ‘Building Monitor’ would gather this information by means of a structured interview with the home owner and/or occupants of the building. The more specific the information is that are input the better the accuracy of the model. But even with almost very little information (year of construction, size of the building, number of occupants) it should be possible to assume the energy use of the building within a range of the above mentioned 20%. Given the additional information about the season, real time information about the weather (from the NetAtmo devices) and the time of date, it should be possible to extrapolate which dimension of the energy use (heating, hot water, lighting, appliances…) is predominant at a specific interval of time.

On average the energy use of the building is currently dominated by heating, which accounts for 29% of the overall energy consumption in Germany, where as domestic hot water only constitutes 6% and the lighting 3%,[5]

[5] Bundeswirtschaftsministerium Berlin, Energiedaten 2015

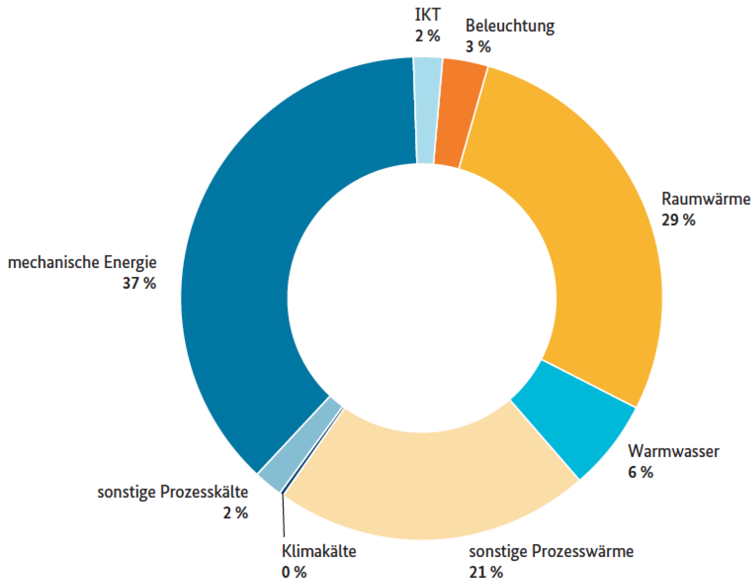

figure 2 energy consumption per scope in Germany 2013 (overall 9.269 PJ),

But contemporary new buildings and refurbished buildings approaching contemporary energy standards have a significantly lower energy consumption for heating due to the better insulation and higher efficiency. 'Building Monitor' might more often be used in those types of buildings. Here a more specific modelling of the energy profile of the building is necessary.

The same is true for information which is irrelevant at a specific time. Heat demand and associated energy use for example might be predominant for many existing buildings with a lower energy standard. Still this information is only interesting and useful during a certain time, when the external temperature is significantly below the internal operational temperature. Therefor, it will not be displayed during summer in general or when the weather is warm enough.

The third parameter for determining the priorities for the display of information after is overall importance and its specific temporal relevance is the possibility of the user to influence the associated energy consumption. Here 'Building Monitor' needs to distinguish between energy use, that is directly or indirectly associated with the users and their behavior and energy use that occurs more or less independent as a consequence of the operation of the building.

Examples for energy use, that can be influenced:

- heat energy use depends on the chosen operational temperature in the rooms
- domestic hot water (DHW) (number of baths, frequency and duration of showering, bathing)

Examples for energy use, that can't be influenced:

- Most ventilation systems operate with a fixed rate of ventilation or are controlled by measuring CO_2-concentration in the air
- Control units for the heating and ventilation system
- Pumps for heating and domestic hot water (DHW) (circulation)

3.2 Dynamic appearance and content

'Building Monitor' should focus on displaying information that is most relevant at a specific time interval. It needs to have a clear informational hierarchy, which always creates an informational context for the user to understand the overall performance of the building and relate the specific information to this context. At the same time the display of information needs to be focused on the most crucial information and highlight the priorities accordingly.

Prioritizing information has two mayor advantages for the system. First the user will only be supplied with the most crucial information and not being overwhelmed by irrelevancies, which helps him quickly to understand the performance of the building. Therefor, he can effortlessly adapt his behavior if he chooses to do so. The second effect might be even more important in the long run. Showing a more or less static display over an extended period of time will result in boredom on the side of the user. It is uninteresting and in a way – little fun – to look at a display of more or less identical information again and again. If 'Building Monitor' on the other hand were to change its appearance over the course of a day, a week and the year, looking at the display would remain interesting for longer. It is one of the mayor challenges of a system like 'Building Monitor' to become and remain a long lasting part of the operational routine of the occupants. Here a more dynamic, specific and ever changing appearance and content could improve the impact of the system.

3.3 Benchmarking

An effective way to evaluate the information displayed is a benchmarking with specific values at a given time interval. 'Building Monitor' creates and specific simulation of the building and its energy consumption. The measured values can be compared to the target values ("*Soll-Werte*"). The system can highlight discrepancies, using for example a color scheme (red being bad, blue being good values). Even high values for the energy use might be not critical if they are below the estimated or calculated values.

3.4 Interaction: Prioritizing according to possible influence of the user

The last parameter to determine how the information is displayed is in how far the user has a possibility to optimize or reduce energy use by adapting the settings of building or his behavior. It makes little sense to confront the user with information that he can not influence. This might even be harmful to the success of the whole system. The success of 'Building Monitor' depends on the acceptance of the users. If they understand that the system will provide them with specific valuable information, they might continuously work with the system and change their behavior and comfort levels accordingly. If ‘Building Monitor’ generates a lot of information that they can do nothing about what so ever, they will abandon the system sooner or later.

Therefor providing relevant and specific information, that the user can relate to his own preferences and behavior is crucial.

BUILDING PHYSICS & ENERGY EFFICIENCY

4 Extrapolation and Interpolation of Energy Demand of Buildings

In the following chapter a computational model will be described for separate energy dimensions.

4.1 Heat Energy

A system that can be used to provide real time information about the heat energy would include meters for heat energy demand, for the heating and hot water. A general system for the heat and domestic hot water (DHW) energy use is based on measuring heat energy in the pipes based on Ultrasounds with an M-Bus meter being able to transmit the data to a central server. In those cases where electricity is used to produce the heat energy (like in a heat pump) a smart meter could collect real time data for the energy production. But in most cases even those systems are combined with non-electrical components, like a solar-thermal panels, and therefor a smart meter is not applicable. ‘Building Monitor’ should be a system that can be put in general use and should therefor not include equipment that can only be implemented in a minority of cases.

In combination with the rest of the necessary equipment for a general heat energy monitoring including additional components like the M-Bus interface would generate extra costs for the product of about 5’000 Euro for a single family house. These extra costs are too high for the price range of buildin.g monitor. Our aim in the project is therefor to use the data available about the building and the measurements of the indoor and outdoor climate to extrapolate the building’s performance.

4.2 Heating

The heat energy is mainly based on these parameters:
- Weather (outside temperature and wind)
- Indoor climate (mainly indoor temperature)
- Quality of the building envelope (insulation, windows)
- Ventilation rate / losses (with or without ventilation system and heat regain)
- Air tightness and infiltration
- Solar gains
- Inner gains
- Efficiency of the heating system

Since in many cases specific information about the last four categories might not be available, the system should extrapolate the energy use based on the temperature difference between inside and outside, which can be measured at each moment in time by the NetAtmo devices. The computational model will only use a simplified mapping of the energy use being based on:

- Weather (outside temperature and wind)
- Indoor climate (mainly indoor temperature)
- Quality of the building envelope (insulation, windows), which will be assets by the energy use of previous years *(consumption data)* or by categorizing the building according to its quality, which can be deduced from the questionnaire that is filled in during the installation of 'Building Monitor'.

Therefor the temperature changes (curve) can be used to map a constant heat energy use according to specific temperatures:

Step 1. HEAT ENERGY DEMAND CONSTANT MONTHLY AVERAGE
Using 100 KWh / sqm * a as an exemplary number for the heat energy demand

Heat Energy Consumption	
100,00	KWh / sqm * a
Average per month	
8.333,33	W / sqm * month

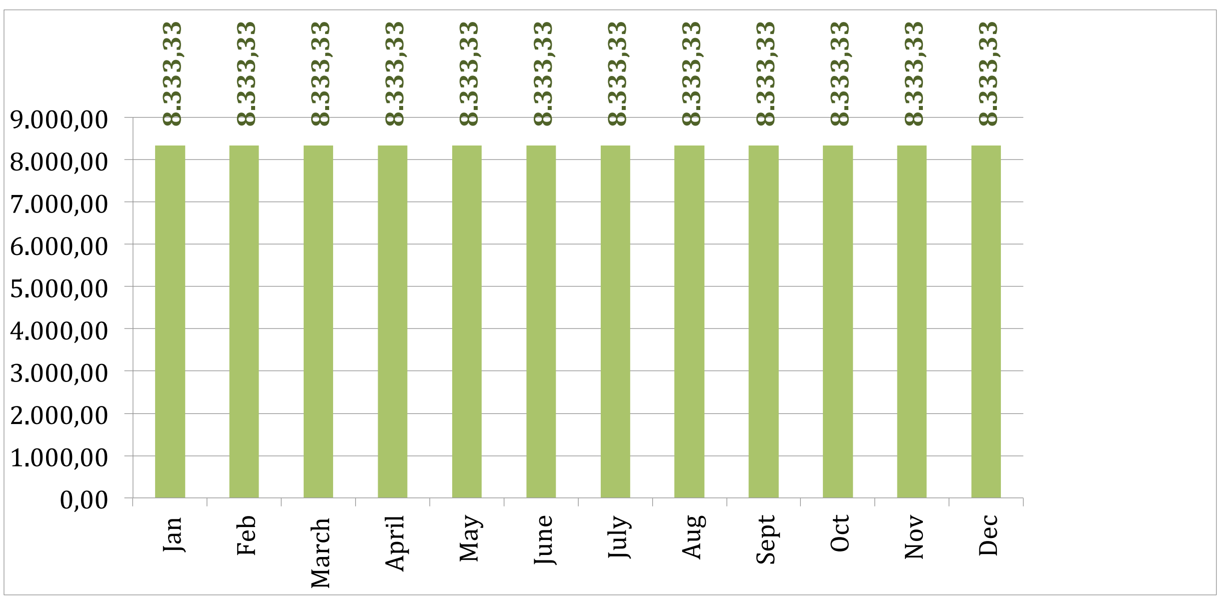

figure 3 example for an even distribution of heat energy consumption per month

This 'curve' represents an even distribution of the heat energy use throughout the year based on either estimated values, which the system would derive from building classification and by comparison to similar buildings. More accurate values can be expected for newer building or refurbished building for which energy simulation (DIN 4108, Din 18599, or similar calculations) are available.

If neither of this information is available, it might be possible to use the records about the energy use of the building in previous though this data should be used with caution since there are many factors that would distort the data:

- The heat energy use depends on the occupant's behavior (room temperature, ventilation and windows)
- In most cases the energy use for heating and domestic hot water (DHW) production can not be differentiated
- The energy use depends on a specific weather profile of each year differencing from a standard or average climate

Step 2. HEAT ENERGY DEMAND
LONG TERM AVERAGE TEMPERATURE

Obviously the heat energy use will vary depending on the weather (seasons) and the energy quality of the building. Therefor 'Building Monitor' will use the standard climate (standardized weather data) to calculate the heating demand for a typical year using long term temperature data:

long term temperature / 20°C (indoor temperature)						
month	day-to-degree ratio		outdoor temperature	outdoor temp. on heating days	month	*expected heat energy demand*
	G20/15	heating days				
	[Kd]	[d]	[°C]	[°C]		W / sqm * month
Jan	569	31	1,7	1,7	Jan	16.831,38
Feb	496	28	2,4	2,4	Feb	14.682,57
March	426	31	6,2	6,2	March	12.608,22
April	287	26	10,1	9,1	April	8.487,70
May	141	17	14,5	11,8	May	4.186,30
June	51	8	17,7	13,2	June	1.516,65
July	15	2	19,7	13,9	July	439,35
Aug	15	3	19,2	13,8	Aug	458,36
Sept	110	15	15,1	12,6	Sept	3.250,44
Oct	294	28	10,2	9,6	Oct	8.699,07
Nov	436	30	5,5	5,5	Nov	12.892,61
Dec	539	31	2,6	2,6	Dec	15.947,35
Year	3378	250	10,5	6,5	Year	100.000,00

table 1 monthly average of heat energy consumption in relation to standardized weather data long-term temperature (1970-2014) (20°C indoor temp.)

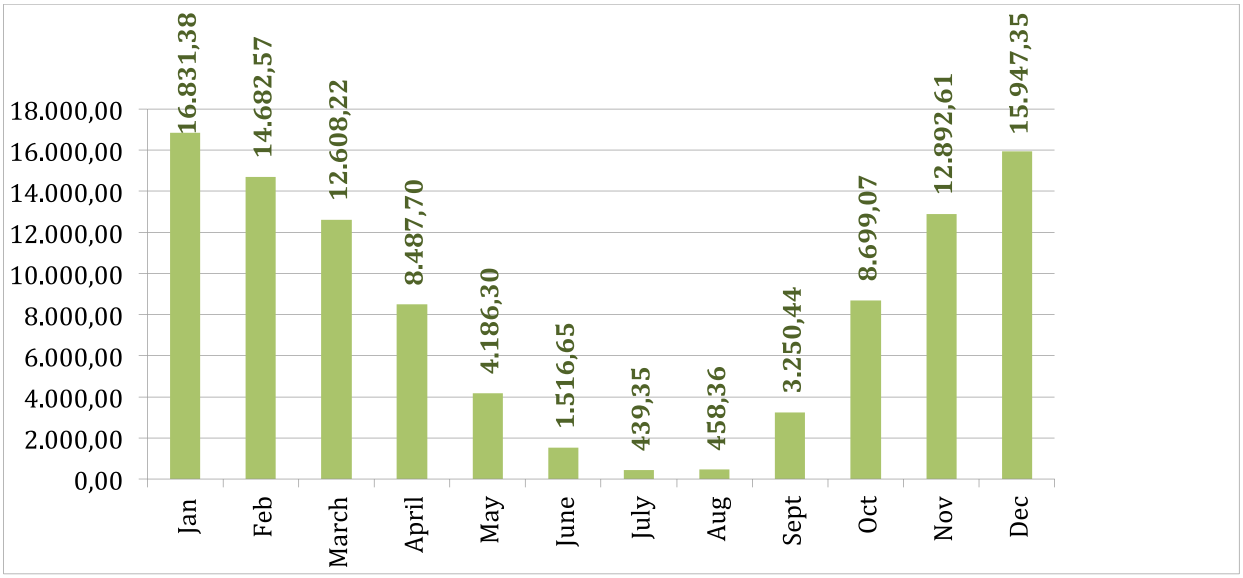

figure 4 monthly average of heat energy consumption (in relation to long-term temp.)

This curve shows the distribution according to the standard climate that is used for energy calculation.

Step 3. HEAT ENERGY DEMAND
ACTUAL (MEASURED) TEMPERATURE

Comparison long term average temperatures (grey) and actual temperatures for a specific year 2014 (green):

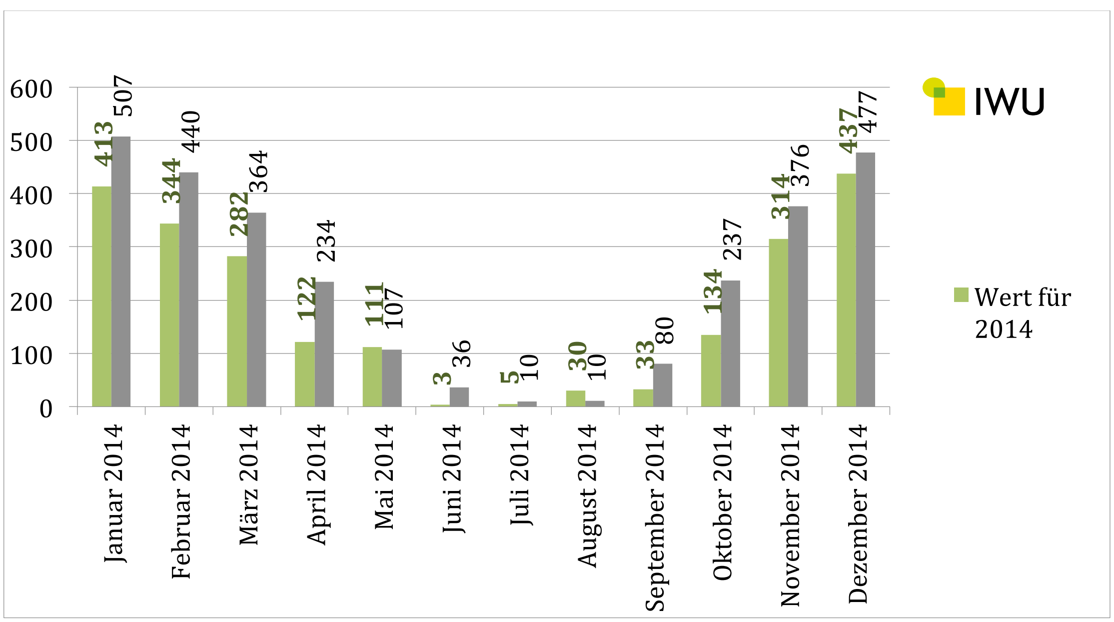

figure 5 temperature differences between long-term temperatures and specific temperatures in 2014 (18°C indoor temp.)

Due to the differences in temperatures in the standard year and the specific year, which result from climatic as well as geographic differences, the more specific heat energy demand would vary from the value in the simulation (DIN 4108, DIN 18599 or similar).

In the example the 100 KWh/sqm*a would translate into 79,67 KWh/sqm*a for the year 2014 which had significantly higher temperatures.

In ‘Building Monitor’ the weather data from the NetAtmo devices can be used for the computational model, which are real time data specific to the location of the building. There is a certain inaccuracy which results from the position of the weather station outside the building, which needs to be under a roof, but outside. Such a location would also have a slightly different microclimate than an open location exposed to wind and weather. This can be compensated to a certain degree by using the average data from all NetAtmos in the near surroundings. Since the inaccuracy is caused by the positioning of the devices it might be, that all NetAtmos show a similar bias. For the final product the data of the NetAtmos showed normalized using data from public weather stations, which have a very high accuracy.

specific temperature 2014 / 20°C (indoor temperature)						
month	day-to-degree ratio		outdoor temperature	outdoor temp. on heating days	month	*expected heat energy demand*
	G20/15	heating days				
	[Kd]	[d]	[°C]	[°C]		W / sqm * month
Jan	475	31	4,7	4,7	Jan	14.057,72
Feb	400	28	5,7	5,7	Feb	11.837,62
March	344	31	8,9	8,9	March	10.194,74
April	166	22	13,6	12,5	April	4.904,96
May	153	21	14,3	12,7	May	4.537,90
June	5	1	18,6	14,7	June	156,89
July	7	1	21,1	13,1	July	204,25
Aug	46	8	17,5	14,2	Aug	1.367,59
Sept	45	6	16,6	12,5	Sept	1.335,02
Oct	176	21	12,9	11,6	Oct	5.218,73
Nov	374	30	7,5	7,5	Nov	11.082,78
Dec	499	31	3,9	3,9	Dec	14.771,12
Year	2691	231	12,1	8,3	Year	79.669,32

table 2 monthly average of heat energy consumption in relation to standardized weather data specific temperature 2014 (20°C indoor temp.)

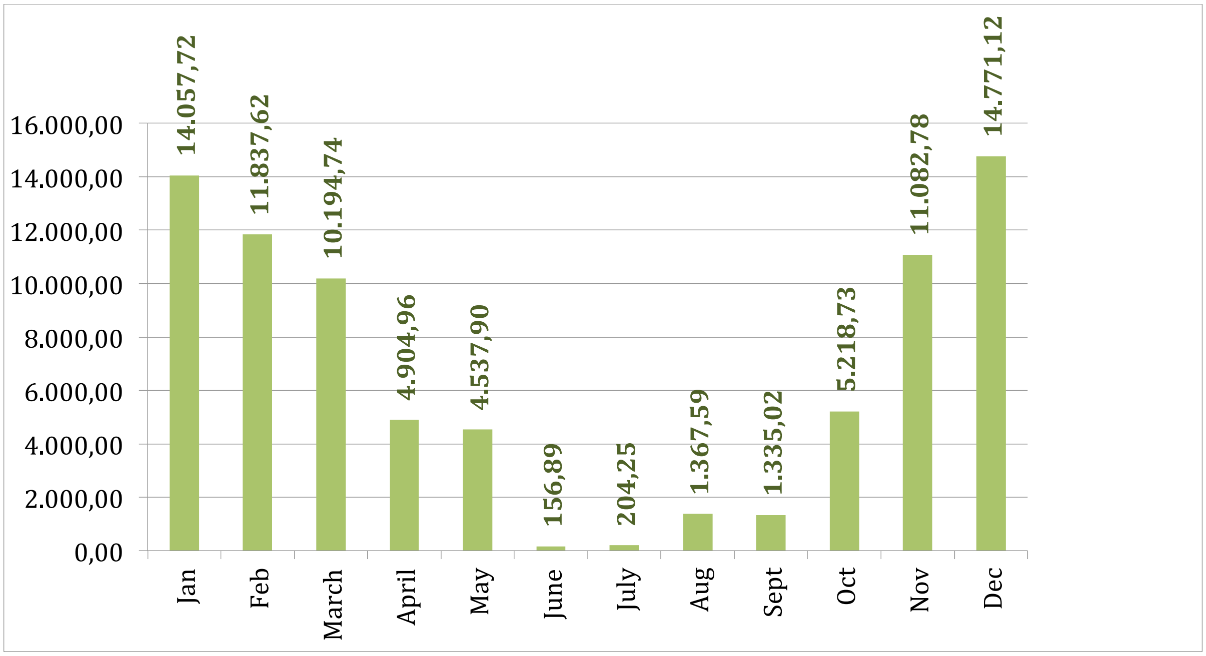

figure 6 monthly average of heat energy consumption (in relation to specific temp. 2014) (18°C indoor temp.)

The curve shows the distribution according to the specific climate in 2014.

Step 5. HEAT ENERGY DEMAND ACTUAL TEMPERATURE PLUS MEASURED INDOOR CLIMATE

Since the heat energy demand is not in depending on the outside temperature but also the indoor climate, mainly the temperature inside the rooms, this information can also be used to make the estimates more accurate. If for example the indoor climate on average is 18°C not 20°C like in the Norm-calculation the heat demand will be lower:

specific temperature 2014 / 18°C (indoor temperature)						
month	day-to-degree ratio		outdoor temperature	outdoor temp. on heating days	month	*expected heat energy demand*
	G20/15	heating days				
	[Kd]	[d]	[°C]	[°C]		W / sqm * month
Jan	413	31	4,7	4,7	Jan	12.222,44
Feb	344	28	5,7	5,7	Feb	10.179,94
March	282	31	8,9	8,9	March	8.359,45
April	122	22	13,6	12,5	April	3.602,50
May	111	21	14,3	12,7	May	3.294,64
June	3	1	18,6	14,7	June	97,68
July	5	1	21,1	13,1	July	145,05
Aug	30	8	17,5	14,2	Aug	893,96

Sept	33	6	16,6	12,5	Sept	979,81
Oct	134	21	12,9	11,6	Oct	3.975,47
Nov	314	30	7,5	7,5	Nov	9.306,69
Dec	437	31	3,9	3,9	Dec	12.935,83
Year	2229	231	12,1	8,3	Year	65.993,45

table 3 monthly average of heat energy consumption in relation to standardized weather data specific temperature 2014 (18°C indoor temp.)

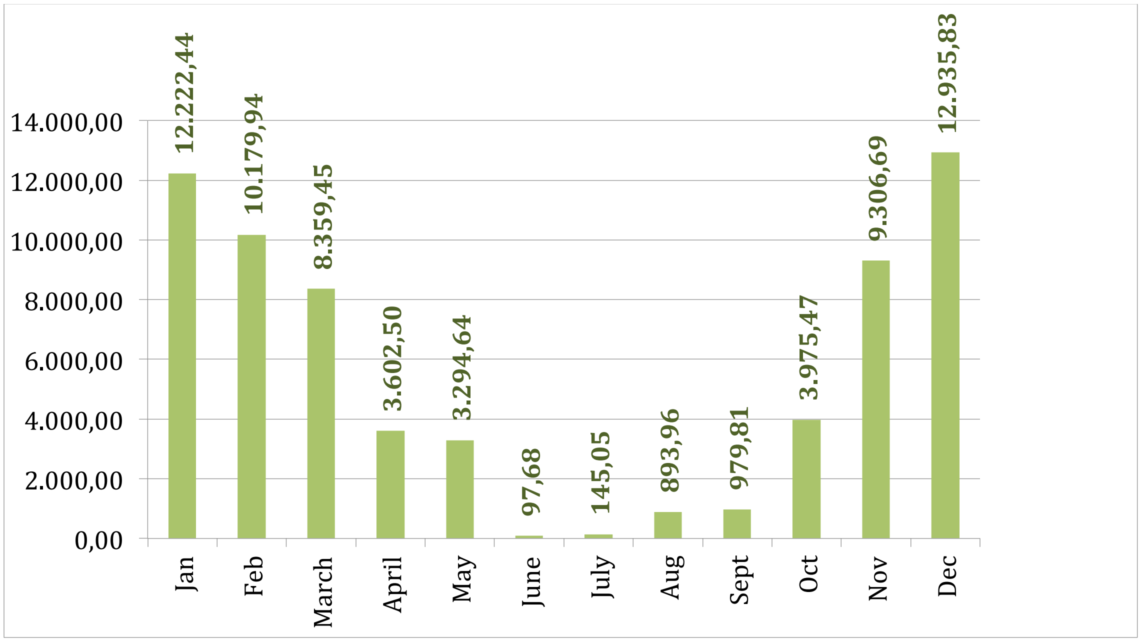

figure 7 monthly average of heat energy consumption (in relation to specific temp. 2014) (18°C indoor temp.)

The curve shows the distribution according to the specific climate in 2014 and an average temperature of 18°C.

Step 6. HEAT ENERGY DEMAND
ACTUAL TEMPERATURE PLUS MEASURED INDOOR CLIMATE AND WINDOW VENTILATION

Based on the measurements of the CO_2 concentration in a room, it should be possible to identify specific events in the room that would influence the heat energy demand. For example a sudden fall in CO_2 concentration in the room indicates the opening of a window or door, increasing the heat energy demand. A high concentration of CO_2 in the room indicated a high presence of people in the room, that would radiate warm and lower the heat energy demand.

It might be possible to translate pattern in those events into parameters that can lower or rise the displayed value.

In the prototype ‘Building Monitor’ the indoor climate data from the NetAtmo devices can be used for the calculations. This is very useful for creating real time data, that can be used in the display of ‘Building Monitor’. Based on the real time data of the NetAtmo devices for each time interval a specific estimate for the actual heat energy use in the building can be estimated.

Depending on the complexity of the calculation, the calculation speed and the speed of the data connection the intervals might be shorter than 15 minutes.

As the NetAtmo devices have a limitation to currently 15 minutes time intervals between every measurement point this is a challenge that is to be solved within the calculation model (see section 9.1.3 foll.).

4.3 Domestic hot water (DHW)

4.3.1 Standard Calculations

In the DIN 4108 and DIN 18599 the energy demand is normalized using an estimate of 12,5 KWh/qm*a. This value can be taken as a base line for the modelling.

In most buildings domestic hot water (DHW) is produced in the central heating system, using the same production as the heating. In many cases a combination of several production systems are combined that both served as energy source for heating and domestic hot water (DHW) (i.e. gas heater plus solar panels). Those systems are more efficient that a separate or decentralized production. As a consequence the data about the energy use throughout the year (energy bill) can not easily be used to describe heating and domestic hot water (DHW) producing separately. Also real time measuring is complicated and expensive (see above).

In most buildings the amount of domestic hot water (DHW) is counted on a meter. Using the distribution of domestic hot water (DHW) energy use in the building and the overall energy use which is measured the domestic hot water (DHW) demand for each unit can be calculated.

In ‘Building Monitor’ it will not be possible to actively retrieve real time data about the domestic hot water (DHW) use. Although there are systems that can be attached to the shower or bath tub that produce real time data, the hardware is expensive (in comparison the overall price range of ‘Building Monitor’) and the installation and integration would translate into additional costs and installation time.

In the test case buildings in Montfoort (further description in section 12) a water metering system in only one of ten houses has been installed for a detailed survey of the energy consumption.
It should be investigated if the potential savings in domestic hot water (DHW) energy use could justify the integration of such devices in a future version of ‘Building Monitor’, but also for reason of costs and effort this has not been realized extensively enough to give a convincing statement.

But in any case, this use of energy might not be reduced as easily at all. Occupants can merely be asked to use less domestic hot water (DHW) by:

- Taking showers instead of baths
- Taking shorter shower
- Not having the domestic hot water (DHW) running, when it is not used

It would need to be investigated how big the potential savings are that can be induced by changing the behavioral pattern.

4.3.2 Specific Estimates

Based on data input by the occupants 'Building Monitor' can make more specific estimates for the domestic hot water (DHW) energy use. The main parameters here are:

- Number of people in the household
- Area per capita, because the standard value relates to a specific residential area
- Sanitary installation (shower, bath tub, size, water saving…)
- Age of occupants
- Behavior of occupants
- Efficiency of domestic hot water (DHW) production, storage, distribution

'Building Monitor' monitor would set up a general model for the domestic hot water (DHW) energy use based in the size of the apartment, the number and age of the inhabitants, as well as the kind and number of sanitary installations. From this a baseline for the energy use in the dimension 'hot water' can be achieved.

Depending on the importance of this dimension as part of the overall consumption 'Building Monitor' could collect data about the behavior of the occupants. This is only useful if the domestic hot water (DHW) use represents a larger part of the overall energy use (25% or more), because it seems not very plausible to significantly change the behavior of the user. It might also be not very popular among the occupants to be told when to take a shower or shorten its duration. Since 'Building Monitor' is highly depending on the cooperation of the users, a positive attitude towards the system is crucial.

Still 'Building Monitor' can model the energy use for domestic hot water (DHW) and collect data about the habits and behavior of the occupants.

4.3.3 Estimates based on occupant's profile

First of all the number of occupants and their age and gender all for the mapping of average domestic hot water (DHW) use to be estimated for each of the units. The energy use resulting from this might be calculated using a average efficiency for the domestic hot water (DHW) production and storage, which depends on the building equipment.

4.3.4 Technical building equipment

For each system a specific efficiency can be expressed as a factor for the most common systems.

- Direct electric domestic hot water (DHW)
- Small decentralized domestic hot water (DHW) storage with internal production (electric boiler)
- Big decentralized domestic hot water (DHW) storage with internal production (electric boiler)
- Decentralized domestic hot water (DHW) production with gas heater
- Central domestic hot water (DHW) production electric heat pump (with storage)
- Central domestic hot water (DHW) production gas heater (with storage)
- Central domestic hot water (DHW) production electric heat pump (with storage) and solar thermal production
- Central domestic hot water (DHW) production gas heater (with storage) and solar thermal production

4.3.5 Seasonal variations

A study in Belgium investigating 8.046 appartments in 390 buildings has shown that the hot water consumption varies with the season because of the outside temperatures.[6] The study is based on the data form a four year period from 2008 until 2012 and indicates that the energy consumption during the summer is lower by 13% than the average and was in winter 12% than the annual average. This variation can also be used to modulate the modelling the energy use for domestic hot water. The more specific to the time period and to the actual application case the information is, that ‘Building Monitor’ would display for the user, the better its chances are to impact this consumption.

4.3.6 User behavior

‘Building Monitor’ can gather information about the behavior of the users in the installation process, as well as on asking them occasionally how often the shower and what is an average duration of each shower. In the final product this might be associated with some playful element like playing a song of a certain duration to measure the time interval. For the prototype this functionality will not be implemented.

4.4 Electrictity - Domestic electricity use

Our definition of ‘domestic electricity use’ in the building includes all use of energy which is related to the operation of the building, such as heating, hot water production, ventilation systems or the control of the building (“*Hilfsstrom*” (auxiliary current) according to EnEV) such as:

[6] Gerin, O. (1), Bleys, B. (2), De Cuyper, K. (3)

- Lighting
- Appliances (cooking, laundry, hair dryer…)
- Home entertainment
- Personal computers and networks
- All other electric use which is not related to heating, hot water, cooling or ventilation

In contemporary buildings the heat demand is dramatically reduced compared to older buildings. Especially for building standards like ‘Aktivplus’, ‘Activehouse’, ‘Passivehouse’ or the general building requirements in Germany in 2016 (EnEV 2016) the heat demand will no longer constitute the predominant part of the energy consumption.

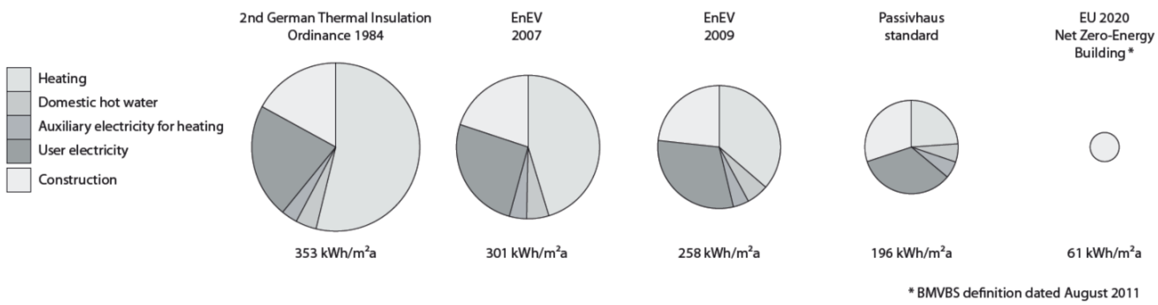

figure 8 average annual demand for supplied primary energy (e.g. from the public electricity grid) for residential buildings built to different energy standards (period of observation 50 years)

Electricity for lighting, appliances, and entertainment will account for the mayor share of the operational energy consumption. Since this energy use is closely related to the behavior of the users and their choices (for example what kind of appliances and lighting they buy), they are particularly important for reducing the user induced energy consumption and carbon emissions.

For measuring the domestic electricity use (mainly lighting, appliances) a smart meter (for example a Smappee) could be used, which does not monitor each individual outlet or circuit but registers a specific pattern or profile of electricity use in the building to certain devices and circuits. Devices as the Smappee or competitors would be attached to the central power input of the building. They are capable to measure the current passing through the power line and hereby identify patterns of change (profiles) in the current. The smart meter must learn (and being told) to identify those profiles in a comparatively time-consuming installation process, in which each device or function in the building must be switched on separately in order to record and identify its specific profile of electricity consumption.

In the foreseeable future (between 5 and 10 years), smart meters will become very common. Besides the possible energy savings the main advantage is that they can be read out from a distance, which dramatically reduces operational costs of the building. For that reason in many households and buildings in Germany conventional electricity meters are being exchanged for those that can be read out using a radio frequency. At present these are only used for generating the annual energy bill. But they have the potential to measure more often to generate for example seasonal or daily profile of every electricity use for each apartment. If a more sophisticated reading devices were to be implemented in the building this technology might be able to achieve the same kind of profiling and extrapolation that a 'Smappee' meter does.

Using the CO_2-concentration measuring of the NetAtmo system, 'Building Monitor' can predict a typical pattern of occupation of the apartment. For example 'learn' that the residents during week days are leaving the apartment in the morning and only return in the late afternoon or evening. This pattern can be used to predict, if the apartment might be occupied or not and adapt the display of information accordingly.

For the prototype of 'Building Monitor' a direct metering for electricity won't be implemented in order to design the simplest possible hardware configuration resulting in a low retail price for the final product. The final product of 'Building Monitor' could include a more advanced version of Smappee might be used or be implemented as additional component by the user's choice. Given the high importance of the electricity use and the comparatively high potential impact that better information and management could have to optimize this energy use and carbon emission an improved technical possible to measure and map electricity use in the building will be one of the most important field of development for future versions of 'Building Monitor'. However the majority of the existing buildings have a lower energy standard. Their energy use is dominated by heating and domestic hot water, which can be addressed and optimized with the above mentioned technology and strategy.

4.4.1 Aktivplus methods for estimation of electricity use for lighting, appliances and entertainment (domestic electricity use)

The domestic electricity use used in 'Building Monitor' will use the methodology developed in the AktivPlus standard for estimating the electrical energy associated with the user. It covers lighting , appliances (cooking, laundry, hair dryer…), home entertainment, personal computers and networks, as well as other electric use which is not related to heating, hot water, cooling or ventilation.

The calculation methods is derived from two different studies, which analyzed data collected in typical buildings for the use of electric energy

- Domestic electricity use for Germany 2014[7]
- Electricity consumption and electricity use of households in Germany[8]

The problem is that electricity use and user behavior varies greatly in practice - both in terms of very different equipment levels with electrical consumers and in terms of individual behavior. In addition, subject to user-specific energy demand / consumption

[7] BMUB et al., Stromspiegel für Deutschland 2014
[8] Hessische Energieagentur et al., Stromverbrauch und Stromverwendung der privaten Haushalte in Deutschland

possibly significant changes during the life span of people and buildings (change of occupation, equipment, fluctuations in the number of users etc.).

In 'Building Monitor' the advantage is that the assumed values which are based on the calculation method can be adjusted to the to real data which is acquired from the user. At a minimum the user will be asked during installation to input the past energy consumption (for building already in operation) and specify the time period associated with this consumption. During operation the user will also be asked to input the information on his or her energy bill. This gives a clear and precise baseline for the overall consumption in a given period and can be specified using the information gathered about the users and the electrical equipment in the apartment. More ambitious users of 'Building Monitor' can voluntarily input additional data points by inputting monthly data. Since no hardware is included in the basic version of 'Building Monitor' to link the meter to the system the user would need to manually input the number he could read from the meter.

In Aktivplus two methods to estimate domestic electricity are used.

- Simplified estimate based on the statistical data and the specification of the apartment (floor area, number of occupants)

or

- Advanced method based on the analyze of the electrical equipment installed in an apartment

4.4.2 Simplified estimate based on the statistical data

The first above mentioned method is based on the analysis of statistical data does not account for the specifics of the application case and the user. The advantage of this methods is that it can be used as a baseline for the electrify use without the need of further information from the user.

The collection and analysis of household electricity in the mentioned extensive studies has shown that in residential buildings, a basic requirement per residential unit (WE), and on this basis per user is an approximately linear surcharge arises. The baseline for the operation of the apartment as such can be translated into a number of 1.4 persons. The average for all existing residential buildings can be described by multiplying with 900 [kWh / a*unit]. Households with a low consumption range at 500 [kWh / a*unit]. For the Aktivplus standard the lower threshold is used as a benchmark (or target value) as an incentive to lower energy consumption. Since the aim of 'Building Monitor' is to model the energy use as realistic as possible the average value of 900 [kWh / a*unit] will be used for the calculation.

Annual electricity consumption per unit = 900 x (1.4 + P) [kWh / a*unit]

If the numbers of occupants in an apartment is not input into the system during the installation process, 'Building Monitor' will assume an average value per person. The average residential area per person in Germany is approximately 45 m². The energy reference area according to EnEV is typically 20% higher than the living space, which translates into this formula for the average occupation:

Number of persons = A_N / 50s^{m2} (residential area)
thus

Annual electricity consumption per unit = 900 x (1.4 + A_N / 50) [kWh / a*unit]

Example:

The following examples illustrate the calculation of the current user and the resultant specific characteristics:

- Example Single family house (EFH):

  An = 180 m², A_N / P = 50 m², WE = 1

  Unit / household electricity use per year: 500 x (1.4 + 180/50) = 2,500 kWh / a

  or 14 kWh / (m²a)

- Example apartment building MFA:

  A_N = 3,200 m², WE = 40 -> 80m² / WE

  Unit / household electricity use per year: 40 x 500 x (1.4 + (80/50) = 60,000 kWh / a

  or 19 kWh / (m²a)

4.4.3 Advanced method

A more accurate and specific modelling of the domestic electricity use can be achieved using the advanced methods which Aktivplus provides in the form of an Excel tool. Here a list of appliances is given for which the user can choose from a variety of technical specifications, frequency and duration of use. This tool is translated into a simplified questionnaire which will be presented to the user during the installation process of 'Building Monitor'. Since the installation process should be as slim as possible the excel tool will be reduced to the most important electricity uses in the apartment.

Example for input of a residential unit:

Auswertung Nutzerstrombedarf: R8

Allgemeine Daten

Projektname	R8	Wohnfläche	147,0 m²	Bezugsfläche
Projektadresse	Rosenweg 8, 72655 Altdorf	Energiebezugsfläche	294 m²	☑ Wohnfläche
		Anzahl der Personen	2 Personen	☐ Energiebezugsfläche
Fertigstellung	2015	Anzahl der Haushalte	1	
		Nutzung als Büro	10,7483%	

Eingabe der Verbraucher

Gerät			EEK/ Baujahr	Effizienz	jährlicher Verbrauch [kWh]	
Trockner	Kondensatortrockner	7 kg	A++		1.314,0	24,2%
Waschmaschine (KW-Anschluss)	60 °C (Baumwolle)	7 kg	A++		603,7	11,1%
Computer	PC	Normale Nutzung			584,0	10,8%
manuelle Eingabe	Hausautomatisierung				438,0	8,1%
Sauna	6,0 kW (5-9 m³)	20 Min. je Saunagang			312,0	5,8%
Geschirrspüler (KW-Anschluss)	13 Gedecke	Sparprogramm (ca. 50 °C)	A++		273,0	5,0%
Kühlen/Gefrieren	Kühl-Gefrier-Kombination	270 l	A++		211,0	3,9%
Computer	Notebook	Normale Nutzung			204,4	3,8%
Herd	Elektroherd	normale Nutzung	A		200,0	3,7%
Router					175,2	3,2%
Drucker	Multifunktionsgerät Laser	Standby			171,6	3,2%
Computer	Bildschirm	Betrieb 28"(71 cm)	A+		146,0	2,7%
Elektronik pauschal					110,0	2,0%
Stereoanlage	Kompaktanlage				109,5	2,0%
sonstiges pauschal					100,0	1,8%
Drucker	Multifunktionsgerät Laser	Betrieb			82,1	1,5%
Haartrockner					76,3	1,4%
Bügeleisen	Bügeleisen				57,2	1,1%
Beleuchtung	Halogenlampen	Personenbezogen			55,7	1,0%
Kaffeemaschine	Padmaschine				43,8	0,8%
Beleuchtung	LED	Personenbezogen			41,8	0,8%
Wasserkocher					40,2	0,7%
Fernseher	50"	Betrieb	A++		32,9	0,6%
Mikrowelle	800 W				20,8	0,4%
Telefon					17,5	0,3%
Fernseher	50"	Standby	A++		2,4	0,0%
Staubsauger	Flächenbezogen		A		0,6	0,0%

Bedarf nach AktivPlus	2.070 kWh/a	Nutzerstrombedarf gesamt	5.423 kWh/a
	14 kWh/m²a		37 kWh/m²a
	1035 kWh/Pa		2712 kWh/Pa
Stromkosten	658 €		######

figure 9 input list of a residential unit in the AktivPlus-"Nutzerstrom-Tool" (calculation tool for the demand of user electricity)

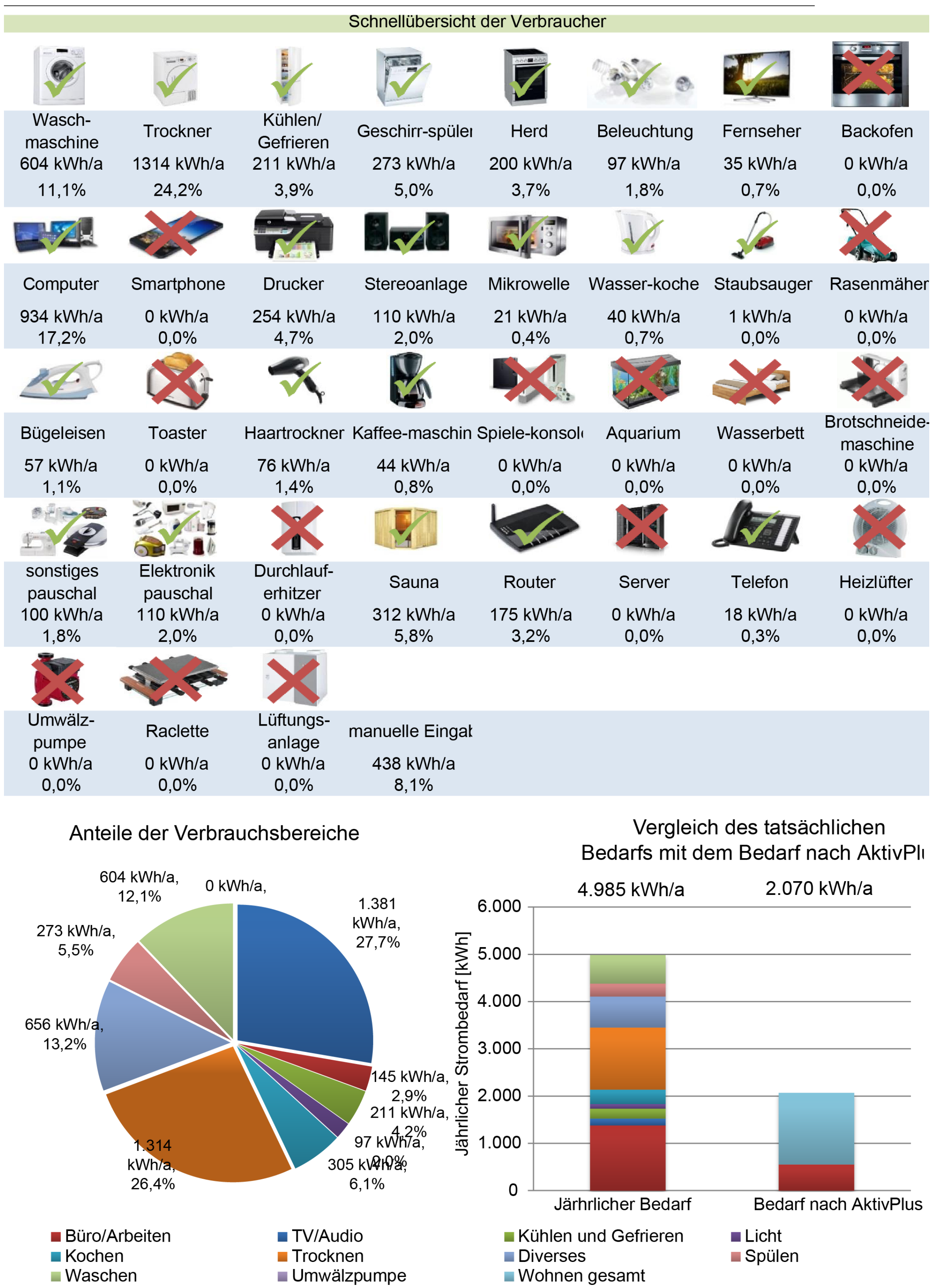

figure 10 input list of a residential unit in the AktivPlus-"Nutzerstrom-Tool"

According to a recent study from 2013 home entertainment is increasingly important for the domestic use of electricity:

Electric Consumer	1996 [9]	2011 [10]	Comments
TV / Audio, Computer, Cell	6.7%,	**25.5%**	
Lighting	9,20%	8.1%	In separate section
Cooking	9,80%	**9.8%**	
Cooling freezing	22.6%	**16.7%**	
Washing, drying, rinsing	10.4%	**12.4%**	
Hot water (water heater)	14.8%	14.8%	In separate section
Air, wellness, garden other electronic equipment	26.8%	**12.5%**	

table 4 Distribution of electricity consumption of households by types of applications 1996 and 2011

In 'Building Monitor' the electricity devices with the highest energy demand will be input during the installation process:

- Television and Audio
- Refrigerator and Freezer
- Washing machine
- Dryer
- Dish washer
- Cooking and backing
- Computer, tablets and networks

Lighting will be addressed in next section. Hot water is not necessarily produced electrically and is also modeled in a separate section.

'Building Monitor' can model the electricity consumption based on this information. The results will be evaluated in terms of their plausibility by comparison to average energy use pattern. If the resulting model differs significantly from the estimated value based on statistical data (see section 4.4 Electrictity - Domestic electricity use) 'Building Monitor' would ask the user to double check the information the input.

During operation the model will be evaluated against the measured data from the electricity meter. If the result is inconsistent with the model further information will be asked from the user. In most cases the actual energy used will be higher than the model, because only a part of the appliances and equipment is covered by the model.

[9] VDEW 1996
[10] EEFA 2013

It would be useful to visual all active electrical systems and appliances with their associated energy use in the apartment for the users in order to help them to develop an understanding how they could reduce it. This list might also be helpful to identify missing equipment or devices which are often in use, but do not appear in the list. At any time the users can voluntarily input further information about existing equipment or devices they newly purchased.

4.5 Lighting

Lighting accounts for about 8,1% of the domestic use of electricity in 2011.[11] The increasing efficiency of modern light sources (halogen, energy-saving light bulbs, LEDs) will probably compensate the higher use of lighting in the residential buildings (bigger apartments, change of life style, higher expectation of comfort). The development between 1996 (9,2%) and 2011 (8,1%) showing a comparatively constant share of the electricity use associated with lighting can be explained by this rebound effect, that higher efficiency is overcompensated by higher consumption.

4.6 Modelling and display of energy use for lighting

The share of the overall energy of lighting is low: 8,1% of the electricity, which accounts on average 30% of all the energy used, translates into about 2,5% of the entire energy use of the building. Taking this into account 'Building Monitor' should not focus on reducing the use of lighting on a day to day basis.
Especially the use of more efficient light sources can lower energy use. Depending on the lighting technology in use a higher efficient light source could save up to 82% of the energy (comparison between incandescent light bulb and LED).

Area of lighting	Energy saving	CO2 savings per lamp per year
Road lighting	HPL → 57% → CosmoPolis	109 kg CO_2
Shop Lighting	Halo → 80% → CDM	115 kg CO_2
Office & Industrial Lighting	TL8 → 61% → TL5	77 kg CO_2
Home Lighting	GLS → 85% → CFLi	34 kg CO_2
LEDs	GLS → 82% → LED	34 kg CO_2

table 5 Examples of energy savings which can be achieved with new lamp technologies Philips Lighting, The Netherlands

[11] BDEW 2013

Therefor it makes sense to analyze how much of the light source in use are already operated with high efficient light technology (LED or Compact fluorescent lamp (CFL)[12]). This could be addressed in the installation process or in the a annual report which ‘Building Monitor’ could produce interpreting the collected data. Here the system could show scenarios of the current situation and possible improvements.

4.6.1 Responsive and interactive display of the energy use for lighting

The aim of ‘Building Monitor’ is to create a model and display of the energy use of the building that is as simultaneous (real time data) as possible. For the perception of the user it is important to only select and display information which is relevant at a specific moment (time interval).
The use of lighting in the building depends (obviously) on the time of day and year and the weather situation. Using the parameters available to the system (time of day and date, geographic location) ‘Building Monitor’ can predict how much light might be used at in an specific time interval and only high light or even display the information about the energy use for lighting when there is a high probability that many light will be used in the building. For example the time of day and date will lead to a typical pattern in which the lighting might be used:

- Winter: Morning and early afternoon, evenings
- Summer: Late evening and night
- Spring and Autumn: early mornings, evening and night

It can also be assumed that at certain times the occupants are asleep and will also not use the lighting even though it is dark outside. The accuracy of the displayed information is not an end in itself. The credibility of ‘Building Monitor’ depends on the plausibility of the displayed information. If the system were to display energy use for lighting during bright daylight or at times when the user is not at home, it might undermine the credibility of ‘Building Monitor’. Therefor those inconstancies should be avoided even if they only account for a little amount of the overall energy use.

[12] It should be mentioned that CFL are more energy efficient than incandescent light sources but have the disadvantage of containing quicksilver and other problematic substances, which have the potential to create greater enviromental and health problems. Also their light profile does not match or even aproxiamte the profile of natrual sun light, which might have a negative psychological effect.

5 Building physics of Well-Being: The computational model of 'Building Monitor'

The indoor environment is described as a combination of the indoor air temperature, the humidity in the air, the air quality, visual and acoustic environment. The indoor environment is influenced by the control of thermostats, window opening and occupant behavior. Humphreys et al. described how people will act to regain comfort if being uncomfortable.[13] As the indoor environment often is linked to the energy consumption, the findings of Humphreys et al. indicate that the energy consumption is controlled by the occupants' control of the indoor environment.

5.1 Room Temperature

The indoor temperature influences occupants' comfort and the energy consumption of the house. Maintaining a high temperature will result in a high energy consumption and vice versa when cooling the house. Occupants' definition of comfort is defined by their perception of the thermal environment.[14]
Occupants' interaction with the indoor temperature happens through some kind of thermostat. Peffer et al. studied how occupants interacted with the programmable thermostats in the US and found that people found them too complicated to use, meaning the potential energy savings wasn't achieved.[15]
Fabi et al. found that the indoor temperature is controlled by the occupants perception of the outdoor temperature.[16] Assuming that the use of heating primarily is influenced by the indoor temperature, Sardiano found that the control of the indoor temperature was controlled by the age of occupants, the number of occupants and households' annual income.[17] Sardianou further found the thermal quality of the building was significant for the use of heating, a finding that was explained by the pre-bound effect. When a pre-bound effect occurs, occupants know how a high indoor temperature will result in a high energy bill and they therefor maintain a low indoor temperature.[18]

5.2 Relative Humidity

The control of the indoor environment is determined by the outdoor temperature.

The relative humidity is an expression for how much vapor the air can obtain. The amount of moisture the air can contain is determined by the air temperature, the higher the temperature the more vapor can be obtained in the air. If the air temperature drops the dew-point temperature can be reached, which can result in moisture in the components.

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[13] Humphreys & Nicol 1998
[14] Frontczak et al. 2012
[15] Peffer et al. 2011
[16] Fabi et al. 2012
[17] Sardianou 2008
[18] Sunikka-Blank & Galvin 2012

The moisture content and the relative humidity are crucial for humans’ health and comfort. The European Standard EN 15251-2007 recommends that the relative humidity is between 25-60%. The upper benchmark is recommended in order to reduce the risk of mold and fungus formation. Mold can grow when the relative humidity is above 70%. However, if a material has been influenced with mold before, it can grow at a relative humidity of 60%.

On the short term, a low relative humidity is not harmful to occupants, but can be very uncomfortable. With a low relative humidity the mucous membrane will dry out making the occupant uncomfortable. Low relative humidity often occurs as a result of air conditioning, as the air is cooling by extracting water from the air.

5.3 Indoor Air Quality: VOCs and CO_2

Particles in the air are described as Volatile Organic Compound (VOC) and Semi Volatile Organic Compounds(SVOC). These particles are released into the air when cooking, burning candles, etc. and are thereby highly influenced by the occupants’ behavior. As quantifying the VOC concentration can be a costly affair, an the CO_2 concentration can be used as an alternative at a much lower cost. The CO_2 concentration is an indication of the human activities and the higher the CO_2 concentration is, the more human activity and the more VOC’s are released into the air. The CO_2 concentration is measured in Part-Per-Million, the outdoor concentration is approximately 390ppm in Europe. The European Standard 15251-2007 recommends that the indoor CO_2 concentration shouldn’t exceed 900ppm (Indoor Environmental Category 2).

The CO_2 concentration is further used to assess the ventilation rate, which in the ‘Building Monitor’ was done using the Decay Method.[19] A study on the ventilation rate in Danish children’s bedrooms showed that it in majority was too low and that it was caused by the occupants not opening the window enough often.[20] Bornehag et al. studied the consequence of a low ventilation rate and found that a low ventilation rate (high CO_2 concentrations) could increase the risk of children developing asthma and allergies[21], a finding which - in relation to the findings of Bekoe et al. - indicates the importance of occupants window opening strategy.

[19] Cui et al. 2015
[20] Bekoe et al. 2011
[21] Bornehag et al. 2005

SOCIAL ASPECTS

6 Conceptualizing the 'Building Monitor'

Basic principles of how to incorporate housing wellbeing, individualizing and interaction into the development of a physical monitoring system

How can residents be induced to advance ecological awareness in regard to their housing environment, reducing the consumption of energy in particular? This question addresses the problem of explaining behavior psychologically as well as that of behavioral modification and control. In what follows, we sketch out the conceptions defining both of these subject areas. What we are pursuing in the end is to develop a technical system, a *'Building Monitor'*, to be operated on smart phones, tablets and computers that serves to elicit and permanently shape environment-conscious and sustainable behavior in the house.

6.1 Current state of research

Commonly accepted research and activities in this area follow a specific paradigm of rationality. What is exclusively studied, first, is the energy aspect: How can the energy consumption in housing be reduced and how do users behave in this regard? Secondly, it is feedback that this approach relies on: Occupants are given information on how much energy has been consumed and how their behavior is contributing to this consumption. Normally this is achieved by technical tools such as *indoor home displays* (IHD), but also by indirect measures, e. g. short term energy billing. It is assumed, thirdly, that such feedback can stimulate a change of behavior resulting in lower energy consumption simply because users have been made aware of the possibility of reducing energy costs. The basic model therefor is a s*timulus-response rational-choice model* (SRRC) of domestic energy behavior.
In the relevant literature and governmental reports it is by now generally recognized however that this model works only in a limited way most notably because it is lacking theoretical foundation.[22] But irrespective of theoretical support, the model has been proven not to be conducive in producing long-term behavioral changes. Nevertheless, the installation of IHDs and the metering of behavior and consumption are still the strategies preferred by architects and energy engineers when sustainability in buildings is meant to play a role.

There is quite a list of findings and recommendations in this respect. They are however not always conclusive or free of contradictions. The suggested findings relate among others to the fact that:

[22] Alahmad et al. 2012; Allen & Janda 2006; Buchanan, Russo & Anderson 2015; Delmas et al. 2013

- direct feedback (via e. g. IHD) is better than indirect feedback (e. g. detailed electricity billings)[23]
- specific, detailed feedback is more effective than summarized consumption statements[24]
- individual and personalized feedback increases the identification of users and results in an improvement of the energy behavior[25]
- interactive intervention increases motivation and triggers environmental learning processes[26]

In terms of quantifying energy savings, several different studies report percentages ranging from 3 to 20 percent of reduction.[27] These figures are however difficult to evaluate and compare as in these studies the housing conditions, house usages and technical facilities vary to a high degree. Controlled experiments with context conditions that are kept constant are practically non-existent.[28]
Moreover, the way in which the consumption feedback is communicated and presented can differ substantially. The information as such can be communicated in many different ways, and systems can be adopted that also include explicit behavioral advice (*calls for action*).[29] Frequently consumption and energy costs and comparison percentages are indicated in real time and not with the delay of protocols. Sometimes the users' behavior is reflected by making the financial gains or losses accessible for a direct reading. Reward systems on the basis of intrafamily competitions, games and the awarding of prizes are other variations.[30] Reports on the effectiveness of these and other forms of feedback are heterogeneous in their results, and they are usually limited to the particular case, even though the claim to empirical generalization is frequently suggested.
What however can be confidently generalized is that environmentally conscious beliefs do not normally result in noticeable cost reductions.[31] As is known from other socio-psychological contexts, ideologies seldom translate directly into genuine action. It has occasionally been tried therefor to give users feedback of the *discrepancy* between their attitudes and their behavior and to communicate to them that they are not acting in accordance with their very own convictions. Following Festinger's well-proven *theory of cognitive dissonance*[32] this information may present a driving force for the change of behavior[33], but systematic studies regarding this are wanting.
It is also generally deemed to be valid that financial incentives can motivate users only to a limited extend, especially when the possible gain is quite small.[34] In buildings that

[23] Carroll, Hatton & Brown 2009; Darby 2006; EEA 2013; Martiskainen 2007
[24] Fitzpatrick & Smith 2009; Martinez & Geltz 2005
[25] Fischer 2007; Lundgren 2002; McMakin & Malone
[26] Fischer 2007
[27] Abrahamse et al. 2005; Darby 2006; Ehrhardt-Martinez et al. 2010; Fischer 2008; Harries et al. 2013
[28] Buchanan et al. 2015
[29] AECOM 2011; Mountain 2006
[30] Rist, Wendzel, Masoodian, Monigatti & André 2011
[31] Becker et al. 1981; Brandon & Lewis 1999
[32] Festinger 1957
[33] Kantola, Syme & Campbell 1984
[34] Buchanan et. al 2015; Carroll et. al 2009

have a high standard of energy efficiency to begin with, the potential savings are in fact normally very small and therefor only of limited motivational impact.
Finally it has to be pointed out that in energy reduction research the aspects of health and individual wellbeing are almost always lacking. Health and wellbeing as incentives do not play any role in existing feedback systems, although in an influential early study, Becker and others (1981) have argued convincingly that feelings of comfort motivate residents to save energy more so than financial savings.

6.2 What the ‘Building Monitor’ is not

The ‘Building Monitor’’s aim is to change energy behavior. This means that the user, interacting with the ‘Building Monitor’, must be encouraged to perform a particular behavior that may well differ from ongoing habits and that should result in consuming less energy.
In order to be active with this in mind, the ‘Building Monitor’ needs to be fed with information about the performance and energy use in the house. Monitoring the physical housing environment is relatively easy if the building is equipped with all sorts of sensory devices and meters for recording temperature, brightness, indoor air quality and noise as well as the different consumption levels of heating and cooling, domestic hot water use, electricity and lighting. Since the use of the ‘Building Monitor’ however should not be restricted to buildings that have this overload of in-build monitoring technology, a novel feature of the ‘Building Monitor’ is to employ *estimation models* that can give reliable information about the performance of a building based on data from only simple recording sources supplemented by statistical generalizations.
But from wherever the ‘Building Monitor’ is receiving its data supply, it must prepare the information in such a manner for the user to see and react upon. In the conventional SRRC model it is assumed that mirroring the metering information suffices to prompt the user into taking energy saving actions. But since this has been empirically challenged all along the line, as we have seen, the ‘Building Monitor’ must employ additional clues for creating the right motivation that will gear the user into modifying her or his consumption behavior. So by no means is the ‘Building Monitor’ a passive device, presenting monitoring data and nothing else. If we want to go beyond the ineffective SRRC feedback model therefor, we should make the ‘Building Monitor’ an *agent* who is encouraging users to alter practices they have grown accustomed to.
Next to motivation and encouragement, users of the ‘Building Monitor’ also need to be given direct guidance as to what to do and how to modify their behavior for improving consumption. This can come in the guise of explicit recommendations (“Go and open the window!”) but also by way of a permanent learning and socialization process. We may be reminded by the ‘Building Monitor’ for instance that it is generally not worthwhile to leave the lights on when not needed or to indulge in an excess consumption of hot water, pointing to the consequences of such environmentally unfriendly doings. If this is conveyed to the user systematically over time, it will gradually heighten her or his ecological awareness, stimulating attitudinal change and subsequent actions.

6.3 Foundations in action theory

Although as a rule that is rarely made explicit, all feedback models on domestic energy behavior that are following the SRRC model are based on the microeconomic theory of explaining collective phenomena. From a microeconomic perspective human agents take rational choices guided by the prospect of possible benefits. Actors dispose of a set of ordered preferences and are guided by expectations regarding the implementation of these preferences (theory of maximizing the subjectively expected utility [SEU]). In addition to their preferences the rationality of maximizing benefits is shaped only by external conditions, i. e. the "world states" to which the expectations refer.

Microeconomic theorizing has been extremely successful as the dominant model of explanation and prediction in wide areas of the economic and social sciences, driving home large proportions of explained variance[35], but it is obviously limited to situations in which the agents are in command of a set of ordered preferences, i. e. that they actually know what they want. Very often however this is precisely not the case. Our actions are only too often guided by the intuition of norms or by pure impulse and are not deliberately rational. Moreover the model remains silent as to where the preferences come from, who actually has them and how they come into being.

For this reason it has been tried for some time now to undergird the microeconomic model by a microfoundation taken from cognitive psychology and thus to free it from the narrow perspective of purely rational choices. In addition to the instrumental maximizing of expected benefits, i. e. rational *cognitions,* also *motivations* and internal and external *constraints* limiting and controlling our behavior need to be taken into account in order to reconstruct our actions theoretically. The *microfoundation paradigm* comprising these three elements has replaced by now the all too simple rational choice model of classical microeconomics.[36] Consequently, microfoundation of behavior implies in particular that the motivational factor and the interaction between cognition and motivation come into play.

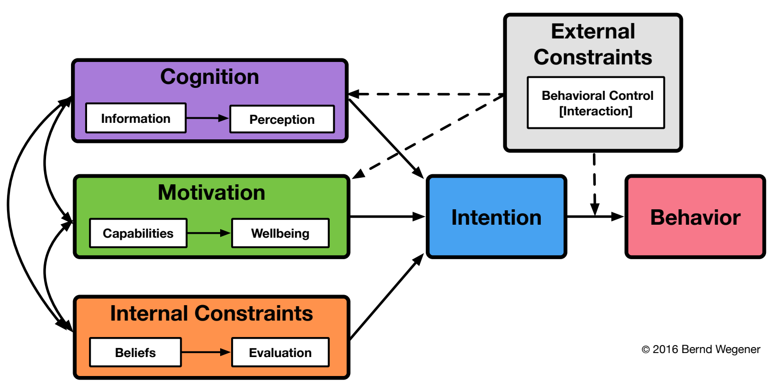

figure 11 pradigm of microfoundation

[35] Becker 1976
[36] Ajzen 2005; Lindenberg 2006 a, b

The challenge in explaining behavior in the microfoundation paradigm then consists essentially in identifying the three triggering factors of behavior - cognition, motivation and constraints - and operationalize them appropriately. With regard to energy behavior at home therefor we are confronted with the question of how to specify the three components we need in order to substantiate the new model. What factors do not yet play a role in the classical SRRC model and should be made part of the new theory?

6.4 Housing wellbeing, individualizing and interaction

In order to overcome the shortcomings of the SRRC model we will introduce and operationalize the following three groups of components into the 'Building Monitor': As motivational element we have chosen the concept of *housing wellbeing*, as external constraints we will make use of a standardization of the types of house users (*individualizing*) and as external constraints we will devise the 'Building Monitor' in such a way as to provoke response behavior by the user and to guide her or him in interactively operating the device (*interaction*).

These three components (which will be detailed below) are not to be specified in individual psychological terms only, but will be geared to newer praxeological approaches in sociology no longer focusing on individual behavior and its rationality but on collective *practices*. The focus of the *practice turn* is not the explanation of behavior and corresponding interventions, but the cultural interpretation of social actions in situations governed by norms. In architectural sociology and the field of consumption theory generally, this approach is represented, among others, by Elizabeth Shove's work.[37] She analyses energy saving behavior quite concretely under the aspects of „seeking comfort", „cleanliness" and „convenience" and describes the routinely exercised collective practices of everyday life in these areas.[38] Even though this approach is not interested in the explanation of individual behavior as such it can provide material for localizing components of the relevant behavior in the energy saving context in order to introduce these components into the 'Building Monitor'.

6.5 Housing wellbeing as motivation

If in the new model ordered preferences and the corresponding maximizing of expectations are no longer in the center of attention, but motivation and the interplay of motivation and cognition, then one has, with our purpose in mind, first of all to define the motivational basis of adequate environmental behavior.
The approach we have chosen is focused on wellbeing, in our case on *housing wellbeing*. Housing wellbeing can be defined as the integrated result of all the physical and non-physical aspects we find essential for feeling well in our home. Wellbeing in this sense is the value that determines our behavior as the expected reward we hope to receive (theoretically congruent with the subjectively expected utility [SEU] frame). The

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[37] Shove 2003; Shove & Spurling 2013
[38] see also Schatzki et al. 2001; Reckwitz 2002; Warde 2005; Strengers & Maller 2015

assumption is therefor that the different dimensions of the evaluation of housing, e. g. Shove's praxeological aspects „comfort", „cleanliness" und „convenience", but also other dimensions, as we have defined them for instance in the *Housing Wellbeing Inventory* (HWBI), can be aggregated to a common housing wellbeing score and that we believe that adequate consumption behavior will enhance this score.[39] Thus the "driver" of sustainable behavior in housing is securing and augmenting wellbeing, not the prospect of saving energy. This is the core of the theory of our approach to the 'Building Monitor'.
What we are proposing here then is a *paradigm shift* [40] in designing the 'Building Monitor'. As the motivational force, we do not rely on feedback alone, as energy saving researchers do, but on enhancing wellbeing. So if we want to prompt behavioral changes in domestic energy consumption we must break away from the classical SRRC feedback model and turn to a more elaborated version that includes housing wellbeing as motivation and causally relevant factor.

6.6 What is housing wellbeing?

Wellbeing can be measured. It is considered to be an attitude: an individual mental evaluation of objects that is reflected in different value dimensions. Assessing housing wellbeing is thus an exercise in attitude measurement.
Following the standard model of attitude measurement in psychology, Wegener & Fedkenheuer (2014) have proposed a multi-component view of housing wellbeing distinguishing between *affective*, *cognitive*, and *conative* (behavior-related) reactions in attitude formation. Measuring housing wellbeing therefor, we must first explore what elements constitute wellbeing for users in these three dimensions. The first results of this empirical exploration, underway since 2011, have been laid down in the *Housing Wellbeing Inventory* (HWBI) as a standardized measurement device for occupants of energy-efficient houses.[41]
In view of developing the 'Building Monitor' however, we additionally concentrate on a different approach, on Amartya Sen's *capability theory* [42]. In the capability approach, we ask what part of our individual possibilities in life have actually been realized in particular situations, for instance in our housing situation. The sum of our individual possibilities represent our *capability set*, termed so by Sen, while the capabilities that are manifest and have been converted into real life are called *functionings*. Capabilities then are what we *could* have and do, functionings are what we have and do effectively. According to this distinction, what we have and do is measured against what we could have and do—that is, we value functionings vis-à-vis our individual capability sets. In the capability approach therefor, wellbeing has a normative side in that functionings that exhaust our capabilities are considered "just" and make thus for our wellbeing.[43]
Housing wellbeing then is the enabling of our capabilities in residential life. To this effect the concept is to be measured as an attitude by assessing a difference: Within the

[39] Wegener 2013; Wegener & Fedkenheuer 2014
[40] Kuhn 1962
[41] Fedkenheuer, Scheller & Wegener 2014
[42] Sen 1979, 1993
[43] Sen 2009

bounds of possibility, what are the features of our home that would be desirable and adequate for us, and which of these are instantiated in reality? So housing wellbeing measurement is the assessment of the discrepancy between our vested ideas of the “good life” in housing and the housing situation we actually have. Wellbeing is given to the extent that this discrepancy is small.

6.7 Individualizing as internal constraint

In conventional housing feedback research it is usually assumed that all users behave alike and are identical in perceptions and behavioral intent. Accordingly, feedback systems operate as one-for-all systems. They do not distinguish household types and different users within the same households providing all with identical information, displays, threshold values and possible action-taking recommendations. But this is hardly in line with reality, since occupants certainly differ in their needs and requisites, perceive their housing environments differently, uphold different values and identify with different environmentalist points of view. Most important is that individuals use their apartments and houses in strikingly dissimilar ways and that they have varying ideas of what purposes their homes should be subjected to at all. Household composition matters as well of course, so does the overall time spent at home.
Considering these differences is the exception in feedback research. An interesting example however reflecting type differences of users is the study by Zhang, Siebers & Aikelin (2012) who distinguish empirically eight *archetypes* of residential energy consumers in the UK (pioneer greens, follower greens, concerned greens, home stayers, unconscientious wasters, regular wasters, daytime wasters, and disengaged wasters). This classification is based very simply on a three-dimensional grid pieced together by the efficiency level of the property, greenness of behavior and, third, the duration of daytime occupancy of the individual. It corresponds with particular type-specific behaviors in energy consumption calling for different content in feedback and the dovetailed recommendations conveyed to users.

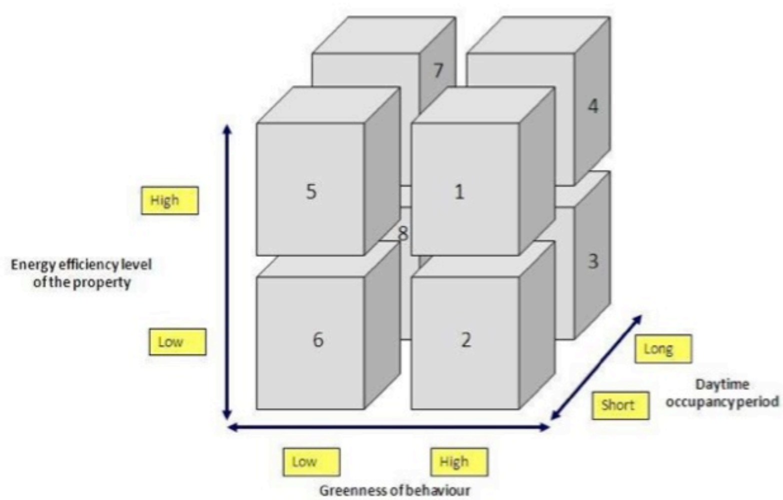


figure 12 Three-dimensional archetype model of residential energy consumers

Other classification schemes that have been proposed are those by Defra (2008) and by Liikkanen (2009). In particular in Liikkanen’s study the consequences are discussed that call for different designs in feedback systems depending on which types of users need to be addressed. As of now, these conceptual reflections however have not been implemented in concrete monitoring devices, something the ‘Building Monitor’ is set up to do.

Considering different user types we speak of *individualizing* the ‘Building Monitor’. Individualizing then means that the ‘Building Monitor’ is selective in passing on information and evaluations, recommendations and suggested alternatives to the user depending on the prior established type of user. In technical terms the ‘Building Monitor’ needs to provide for particular path-dependent filter strategies setting different standards for different groups of occupants. To this end, the ‘Building Monitor’ is essentially of a many-in-one variety.

6.8 Personalizing the 'Building Monitor'

Extending the Zhang, Siebers and Aikelin approach, what follows is a tentative list of user type and housing features that should be considered for customizing the 'Building Monitor' for individual users. The setup process for the device then would involve these 10 steps:

1. *Selecting a user name*

2. *Selecting program type*
   a. Quick Start ("feedback only") ➤ go to step 10
   b. Customization ("recommended") ➤ continue with step 3

3. *Building classification*
   a. Floor plan
   b. Energy efficiency
   c. Domestic appliances

4. *Household classification*
   a. Composition
   b. Economic background

5. *User classification*
   a. Ecological awareness
   b. Health status
   c. Daytime occupancy
   d. Housing preferences

6. *Domestic consumption style (baseline)*
   a. Heating
   b. Lighting
   b. Ventilation
   c. Cooking habits
   d. Domestic hot water use
   e. Electronic appliances

7. *Assessing the baseline housing wellbeing*

8. *Goal setting*
   a. "Starter"
   b. "Normal"
   c. "Ambitious"

9. *Selecting a scenario*
   a. Recommended scenario
   b. Alternative A (not including household members)
   c. Alternative B (including only selected household members)

10. *User interface adjustments*

For the different classifications of buildings, households and users as well as the assessments of style and wellbeing variables, sets of operationalizations are available that have in part already been tested.[44]

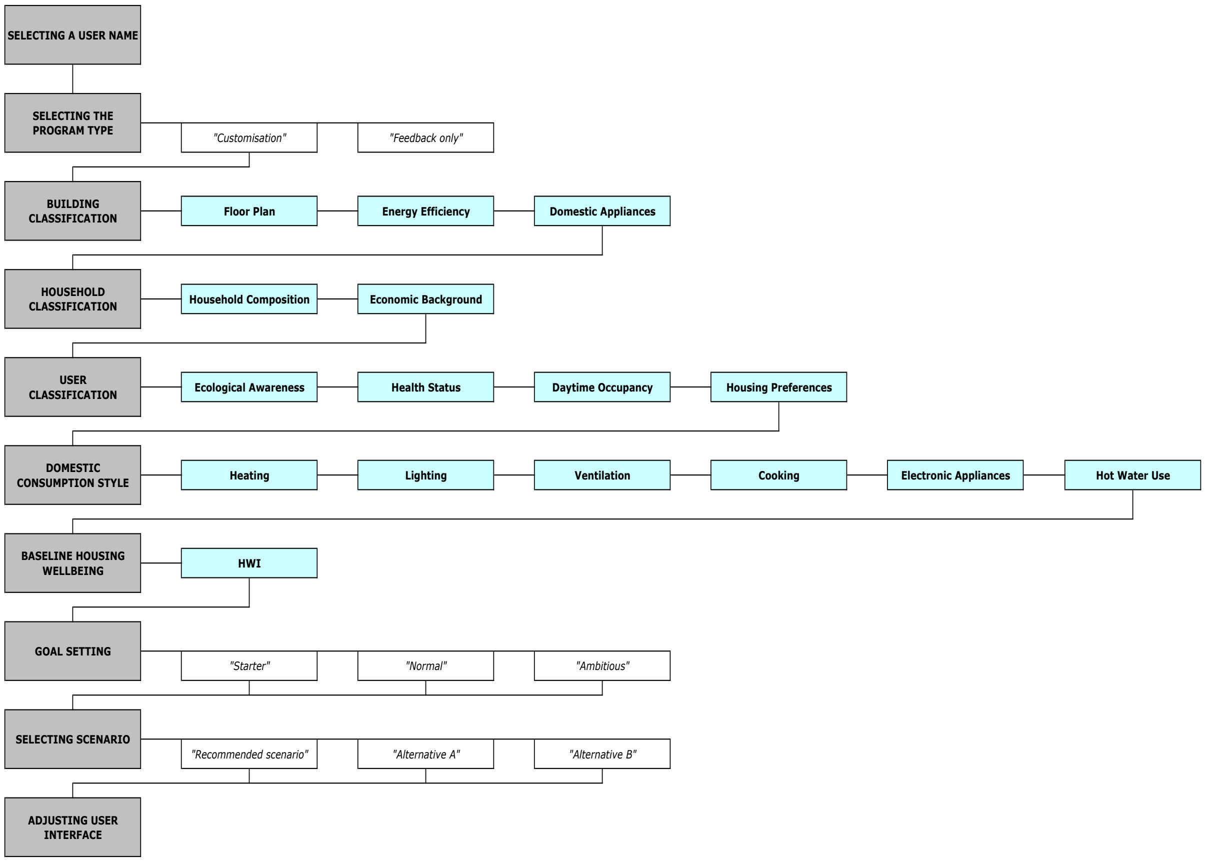


figure 13 Personalization schema for the 'Building Monitor'

6.9 Interaction as external constraint

There is ample empirical evidence that interaction and responsiveness in displaying feedback are facilitating features of housing feedback systems.[45] People not only want to be addressed individually, they also want to respond and take actions individually. Thus it is not only feedback but the *interaction* with the feedback giving device that arouses interest in the user.

[44] Wegener & Fedkenheuer 2014; Fedkenheuer et al. 2014
[45] e. g. Fischer 2007

On the one hand, this interaction refers to the purely technical aspect, i. e. the way of transferring information and the possibility of intervening in the control of the household technology. With interaction however we also mean the inclusion of other members in the household, provided such exist, with the ‘Building Monitor’. Both forms of interaction have a motivational effect on the energy-relevant behavior. However they also represent certain externally added conditions - external constraints - by limiting and controlling the behavior. How to include other household members in the ‘Building Monitor’ and make them interact, will be one of the challenges of the continuing research program of the ‘Building Monitor’.
In the ‘Building Monitor’, feedback loops, individualized recommendations, comfort inquiries, behavior confirmations and also encouraging messages can be integrated to relay the user a feeling of continuous “attention” from the device. Furthermore, the inclusion of other household members is also provided by presenting their behavior to the individual user so that each household member can relate her or his own behavior and the progress made in energy saving to that of the other individuals in the house. In this way, it becomes clear that sustainable energy behavior in the house is a *collective* task - a further aspect that has hardly appeared in feedback research thus far.

IMPLEMENTATION

7 Concept

The prototype version of 'Building Monitor' is supposed to be a proof of concept application. As the specification of what 'Building Monitor' is, was actually one part of the pathfinder project phase, the main focus on developing the software prototype was to outline the basic software architecture and to support and test the findings of the Climate KIC 'Building Monitor' project.

Therefor the focus of the software design was not to build a ready-to-ship end product, but to find a suitable software architecture, which supports the goals of the project and enables further developments and enhancements.

The following section will outline at first the concept of the 'Building Monitor', the challenges and derived requirements from a software design's point of view.

The section '*Prototype'* will give insights on the parts that were implemented in the prototype version of 'Building Monitor', the hardware that has been evaluated and tested to measure the indoor and outdoor temperatures.

8 Methodology of monitoring & displaying information

8.1 Displaying information

'Building Monitor' is an end user product. Although it would be deployed with bundled hardware components, it is its primary nature to be a software product.

Rather than providing and distributing it as a downloadable software package, which would have to be locally installed on some user's computer, dealing with various operation systems and versions, 'Building Monitor' should be designed as a *Software-as-a-Service* (SaaS) product.

As such, 'Building Monitor' would be mainly operating from a central platform in the internet and could be reached by using thin clients, like web browsers or even specialized mobile device apps, which could serve as front ends. A goal in designing the basic software architecture was to stay open for the actual clients who are connecting with 'Building Monitor'.

For end users a new monitoring product should be easy to setup and almost instantly be able to begin its work – monitoring and giving feedback on energy performance and housing well-being.

Furthermore, it can be expected that 'Building Monitor' has to manage a huge amount of measurement data. It needs to be able to process this data in adequate time and simultaneously serve requests from users' interacting with 'Building Monitor'.

The architectural styles to be chosen must therefor allow openness for further scaling of the application, which would be suitable to run 'Building Monitor' on multiple servers, if necessary.

8.1.1 SaaS

SaaS is an abbreviation for *Software as a Service*. Its intention is to offer software services centrally from a server via the internet that can be accessed by any common web browser.

Users of SaaS usually have to purchase a license instead of a software package in order to use it. Because 'Building Monitor' depends on bundled hardware, the purchase of a license is not necessarily required. Users can only use the services, if they are in possession of a valid identifier for the bundled hardware. In case of the prototype version this would be possible by providing the Serial Id of the Netatmo Weather Station.

Another benefit of using a SaaS distribution model is that packaging and distributing the software for various operation systems and versions is not required. It can be used by anyone who is able to access the internet from his or her home.

8.1.2 Architectural Styles

'Building Monitor' is built on several software architectural styles and software design patterns to enable flexibility and future extensibility.

8.1.2.1 Layered architecture

Layered Architecture separates different groups of classes by defining the relationships between them. Common layers are usually the *User Interface* (UI), *Services*, *Domain* and *Infrastructure*. Layers are typically organized vertically. Any lower layer does not depend on any higher layer. This style makes it easier to refactor parts of the application or to add new features to it without being bound to other layers and objects. While the application layer drives the processes and workflows of the application, the domain layer contains the essential domain specific logic of the application. The domain layer is kept independent from the other layers. Supporting libraries or concrete technical implementations, like persistence, message handling or connections to external services are located in the infrastructure layer.

8.1.2.2 Client-Server Model

Client-Server Model is typical for web applications. Multiple clients usually communicate with a server through services by exchanging messages in a request-response pattern.

This separation allows the use of different kind of clients, which could be implemented with independent technologies, e.g. a web browser client or a mobile phone app.

8.1.2.3 REST API

REST stands for representational state transfer. It is a single uniform interface to separate a client from the server application. This interface specifies queries and commands as entry points into the application from the outside.

Using *REST API* supports the nature of the *Client-Server Model*. Frontends can be implemented independently using *REST API* to communicate with the backend of ‘Building Monitor’.

8.1.2.4 Service Oriented Architecture

Services bundle related functionality to solve individual tasks of the application. They act as gateways to the functionalities of lower layers by concentrating the knowledge about how the lower layer objects have to be used.

8.1.2.5 Event driven messaging

Event driven messaging loosely couples independent units of the application.
One object of the application can emit events to inform other objects about things that happen. The other objects can then decide if they want to react with further actions. In this way the different parts are not depending directly on each other.

8.1.2.6 Modules

‘Building Monitor’ is structured with several modules. A module groups related classes, which handle specific aspects of the application. Modules aren’t bound to a specific layer; in fact, they are often spread across multiple layers.

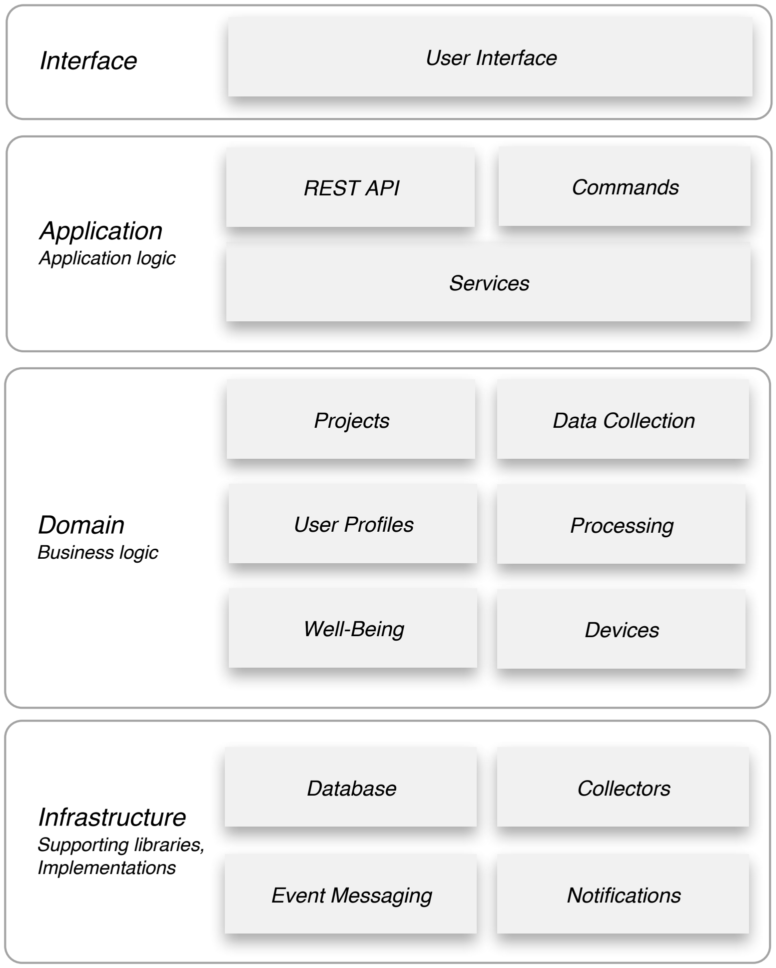


figure 14 modules of 'Building Monitor'

9 Data Model of Monitoring

'Building Monitor' needs to be able to process multiple tasks. The major tasks are to

- interact with users via a *User Interface*
- periodically collect measurement data from the monitoring hardware in the background
- process and evaluate all the gathered data in the background
- derive information about housing wellbeing from users and measurement data
- communicate by sending notifications, invitations or reminders to the users

These tasks can be grouped into several individual aspects of the application.

- Management of a Monitoring Project
- Device handling
- Measurement data collection
- Data processing and evaluation

9.1 Management of a Monitoring Project

A Monitoring Project has to cover all the data from one residential unit, consisting of at least one user account, user profiles of the residents, configuration settings, building and apartment properties, information about the installed hardware and the measured data, which has to be collected and aggregated over time.

Initially the project will have to be set up by a project owner. A step-by-step questionnaire will enquire for all the necessary details and customizations about residents, communication settings, building and apartment parameters and available measuring devices.

The account of the project owner needs to be set up during creation of a project and assigned with authentication credentials. Before using 'Building Monitor' a user needs to login first. The login will be valid only for the current browser session, but can be remembered, if requested, in a permanently stored browser cookie to avoid authentication each time a new browser session has started.

During setup, 'Building Monitor' will ask for further resident respectively family members. Additional accounts can be created for them. This will give them access to the project as well and let them individually participate on surveys about housing wellbeing.

Setting up measuring devices will be as easy as possible. Somehow 'Building Monitor' will have to read data from it, so some kind of credentials to access the data will be necessary to configure within a project for individual hardware devices.

Since these devices can be installed anywhere in the building, additional information about the location of a single indoor device are necessary to distinguish between different room types, like bath, living room, sleeping room, etc.

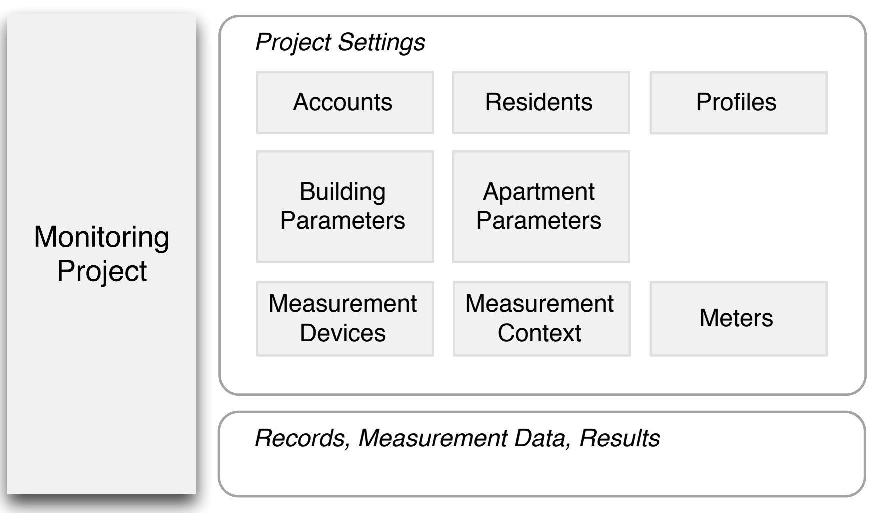


figure 15 Covered areas of a Monitoring Project

9.1.1 Device Management

Internally, 'Building Monitor' abstracts measurement hardware by introducing objects of *Devices*, *Meters* and *Measurement Contexts*. A *Device* represents a single hardware measurement device, which is being assigned to a *Building* or an *Apartment*. Such devices often consist of multiple gauges for different measurement aspects. For example a weather station may be one single device, but measures temperature and humidity. In 'Building Monitor' these gauges are called *Meters* and are bound to one *Device* and are assigned to a *Measurement Context*, which for example would be temperature or humidity.

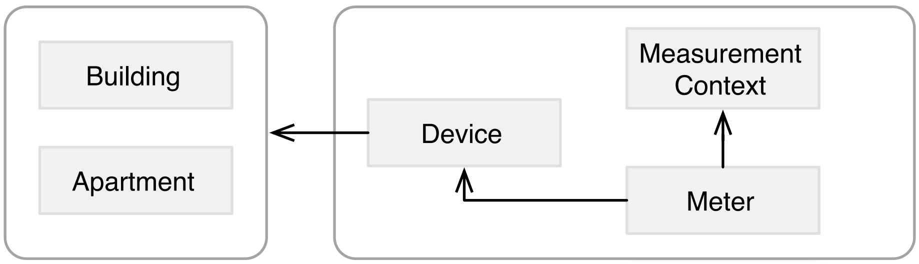


figure 16 Devices are assigned to the building or a specific apartment. They consist of Meters for different Measurement Contexts

For each *Device* a user has also to specify how 'Building Monitor' can retrieve measurements from the device. Therefor another abstract concept has been established: *DataProviders*.

A *DataProvider* is a programming interface, which allows the specification of a method to retrieve measurement data from a *Device*. A simple generic *DataProvider* is the *ManualEntryProvider*, which allows a user to manually enter readings from a local gauge.

Other *DataProviders* depend on specific measurement hardware. 'Building Monitor' has at least one additional *DataProvider* supporting the bundled hardware, which is deployed with the 'Building Monitor'.

A *DataProvider* needs to be configured for each of the device's meters before it can be utilized. For the *ManualEntryProvider* a user will have to configure a default unit of measurement and how the entered reading value has to be interpreted - as measured value or as a counter value.

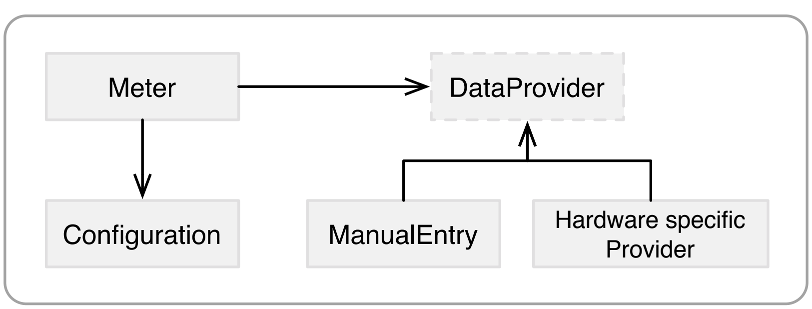


figure 17 Meters are configured for a specific DataProvider

9.1.2 Measurements

The retrieval of measurements will be handled by methods specified by the chosen *DataProvider*. For the special case of manually entered readings, the record will be directly added to the measurement repository. For all other cases retrieval is being dispatched to a *Collector* process.

9.1.2.1 Collector

The *Collector* process in 'Building Monitor' is designed to run in the background. The process will be triggered to run every 15 minutes.

It then asks all registered *DataProviders* to collect new measurements for assigned meters. The method a single *DataProvider* utilizes to retrieve data from a device depends on the hardware. For one device type the data can be retrieved directly through an API from the devices. For other devices the data may only be retrieved through a special cloud service from external servers.
After this process is completed a *DataCollectionCompleted* event is being raised to notify other 'Building Monitor' components.

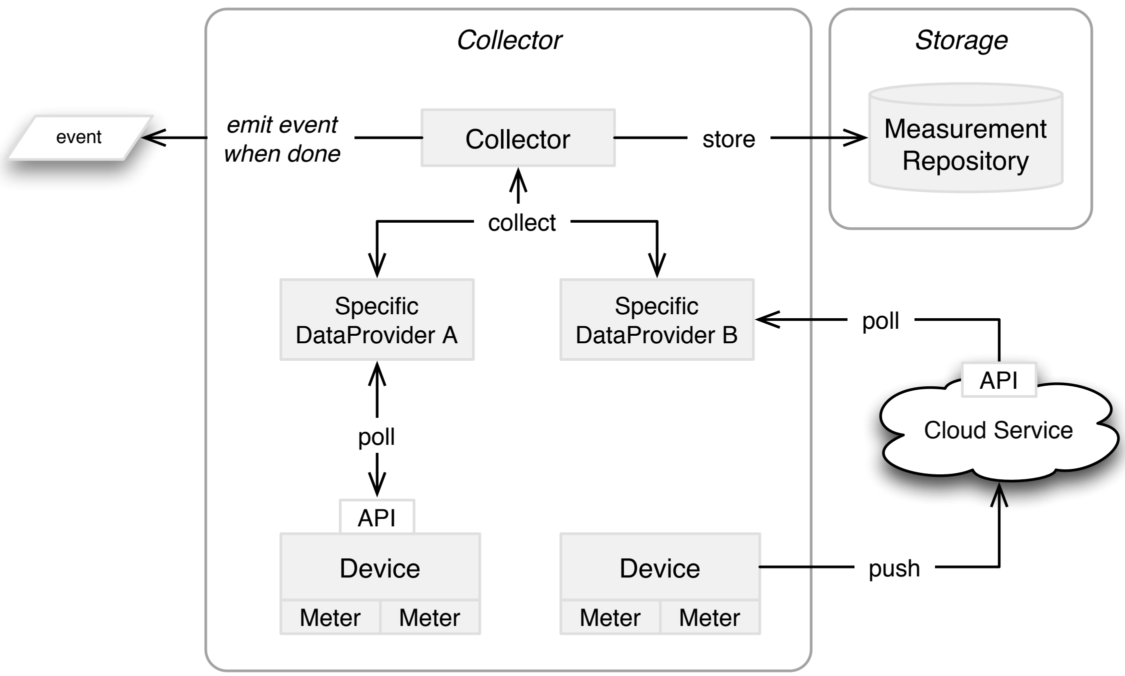


figure 18 Data Collection Process

A Collector triggers two specific *DataProviders* to collect measurements. *DataProvider* can implement different methods to retrieve measurement data, depending on the used hardware. When the process is completed, an event is raised to inform other components in 'Building Monitor' about it.

9.1.2.2 Acquired measurements

The acquired measurements will be persisted in the measurement repository. A single *AcquiredMeasurement* consists of a timestamp, the measured value and its unit. All *AcquiredMeasurements* are assigned to the Meter from which the records were retrieved.

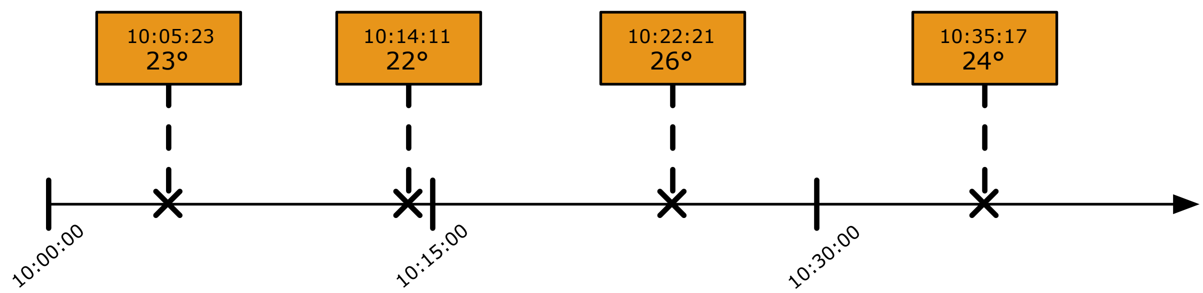
9.1.2.3 Normalization

On a second step the *AcquiredMeasurements* will be normalized. Normalization is the process of

- applying temporal parity and progress on a series of measurements
- interpolating gaps within a series of measurements
- aggregating measurements into small unique time slots

Applying temporal parity and progress on a series of measurements

While a series of measurements for one meter usually contains measurements with different time intervals, each timestamp will be assigned to a fixed 15-minute time slot. These time units assure that the data may later easily be compared.



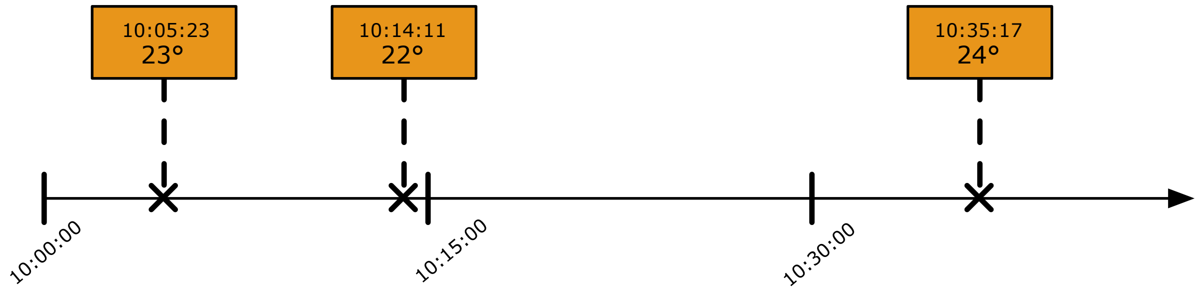
Time stamp	Time slot	Value
2015-10-01 10:05:23	2015-10-01 10:00:00	23°
2015-10-01 10:14:11	2015-10-01 10:00:00	22°
2015-10-01 10:22:21	2015-10-01 10:15:00	26°
2015-10-01 10:35:17	2015-10-01 10:30:00	24°

figure 19 Assigning timestamps to time slot units

Interpolating gaps

The second task of normalization deals with the handling of gaps in a series of measurements over time, which can occur mainly due to power loss or loss of internet connection of one metering device. A gap is present within the data when the difference of two sequential measurement timestamps exceeds at least the length of the minimum time slot size, multiplied by two.

This problem is solved by the interpolation between the last recorded measurement before the gap and the first one after the gap. For each time slot between these two measurements an artificial measurement will be inserted and assigned an interpolated value.



Time stamp	Time slot	Value
2015-10-01 10:05:23	2015-10-01 10:00:00	23°
2015-10-01 10:14:11	2015-10-01 10:00:00	22°
2015-10-01 10:35:17	2015-10-01 10:30:00	24°

Time stamp	Time slot	Value	Value (interpolated)
2015-10-01 10:05:23	2015-10-01 10:00:00	23°	23°
2015-10-01 10:14:11	2015-10-01 10:00:00	22°	22°
	2015-10-01 10:15:00		**23°**
2015-10-01 10:35:17	2015-10-01 10:30:00	24°	24°

figure 20 Filling up gaps with artificial, interpolated measurements

As when applying temporal parity, interpolation also assures the comparison of measured data because for any time slot within a given time frame, a value will always be present.

Aggregating into minimal time slots

As a last step *Normalization* will aggregate multiple values within a single time slot into one aggregated value. The aggregation method is to calculate the average of those values.

Time slot	Average
2015-10-01 10:00:00	22.5°
2015-10-01 10:15:00	23°
2015-10-01 10:30:00	24°

figure 21 Aggregating measurements of same time slot

The normalized data will be added to a separate measurement repository for normalized values. 'Building Monitor' will base all further calculations on this normalized data.

9.1.3 Data Processing and evaluation

Multiple processing modules handle data analysis and processing in 'Building Monitor'.

A processing module is at first an abstract concept, which targets a specific aspect or dimension, which shall be analyzed or processed. It shall concentrate on only one aspect or dimension. That way, multiple processing modules can be implemented separately in 'Building Monitor' and easily extend the application's spectrum on analysis and processing ability.

In the end, each processing module can store its results into repositories for different aspects from where the data can be either further processed by other processing modules or prepared to be presented to the user through the user interface.

There are three different types of result a processing module can produce.

- Results which reflect measured values
- Results which reflect simulated values
- Benchmark values or more generally boundaries

Each result or benchmark value is constrained to a specific dimension and a time slot. Dimensions represents aspects of the housing, like *Indoor* and *Outdoor Temperature*, *Pressure*, *Energy for Space Heating*, *Electricity*, *Domestic Hot Water*, etc., but could also represent non-physical aspects, like a *wellbeing score*.

Adding a new result or benchmark value to the repository will also aggregate them into higher time. The aggregation ranges from 15-minutes up to yearly time slots.

- 15-minute (no aggregation)
- 1 hour
- 1 day
- 1 month
- 1 year

Aggregation is done either by computing the average or the sum of all values within given time slot. Which method to use, depends on the type of dimensional data being aggregated.

In ‘Building Monitor’ processing modules are designed to start working when a specific event has been emitted. If a processing module gets informed of a certain event, for example the generic *DataCollectionCompleted* event, it notifies when this event was raised by another component. The event itself contains further information that a processing module can base a decision on either to proceed or to ignore the event.

In this way the processing modules are not bound to a specific strict procedure, but can be loosely coupled with other components. Since processing modules can raise events by themselves, it is even possible to chain multiple processing modules that can work on different aspects of the same source data or the resulting data from the previous processor.

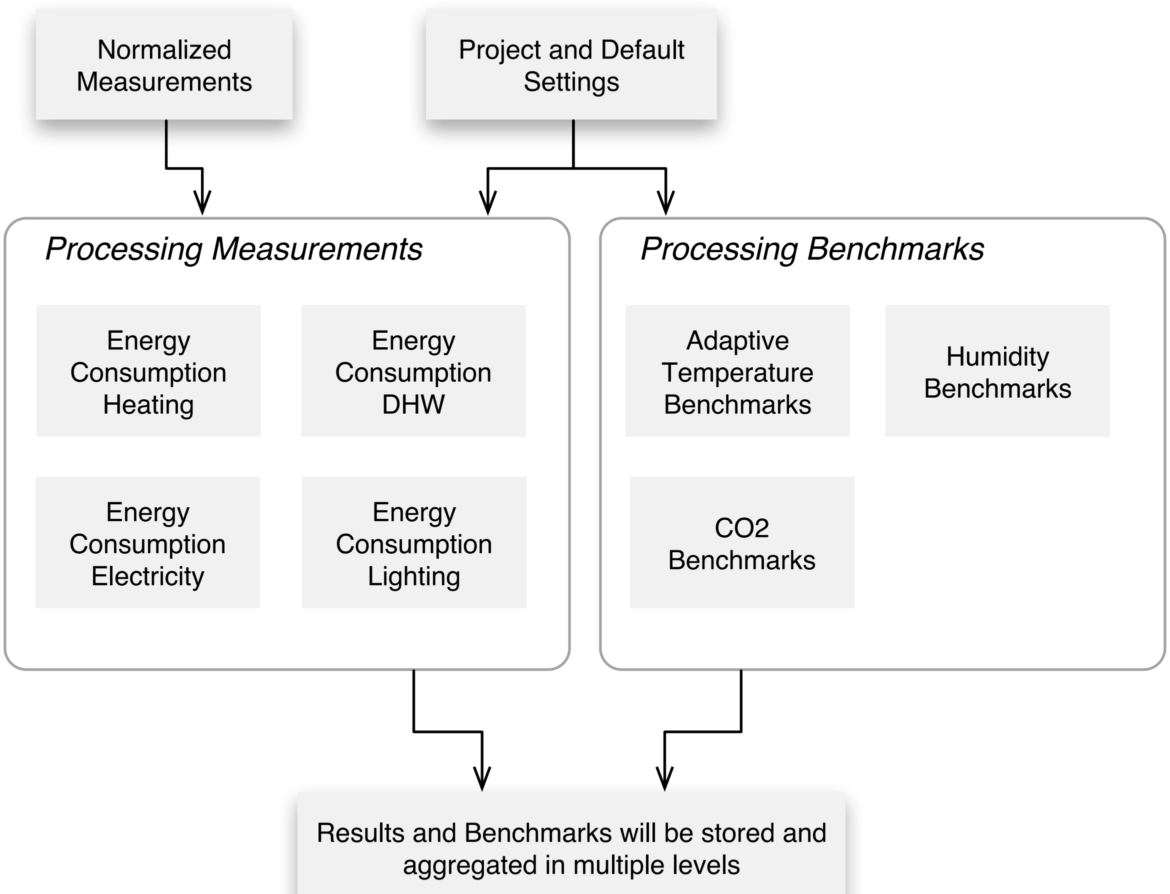


figure 22 processing modules

10 'Building Monitor' Prototype

10.1 Software Implementation

The prototype version of 'Building Monitor' was implemented based on the programming language PHP 5.6. For the application container the popular open source framework Symfony2 was used.

The Database Management System was chosen to be PostgreSQL 9.4, also a very popular open source DBMS.

The implementation of the prototype has been concentrating on the concepts of application design, collection and processing of measurement data. At the beginning of the project there were also some investigations in developing a user interface that you can roughly see in section 11. Since it became notably that the strategy in how 'Building Monitor' has to interact with the users would be part of the findings in the pathfinder phase, the interface is only a very first and immature draft of screen design.

The following sections describe the evaluation of the utilization and how the retrieval and processing of the data can be achieved.

10.2 Hardware: Netatmo Weather Station

'Building Monitor' relies on a small set of hardware components. The prototype version utilizes the Netatmo Weather Station to measure indoor and outdoor climate data of the building. The Netatmo Weather Station is capable of measuring temperature, pressure, relative humidity and CO_2 through different hardware modules, which have to be installed on the inside and outside of the building. With the Weather Station it is possible to add further indoor modules to be able to measure the indoor climate of different rooms.

The hardware modules of the Weather Station measure data in short periods of time (approximately in 5 minutes' intervals). The measured data will be immediately sent to Netatmo servers where they will permanently be stored. Netatmo also provides a public REST API to allow third-party applications to access the devices and measurement data.

10.2.1 Partner API

For third-party service providers, who want to bundle their products with Netatmo services, Netatmo offers a special Partner Program. This program grants access to the bundled devices for registered third-party applications through a Partner API.

This enables 'Building Monitor' to get access to the device and measurement data of bundled devices. All the system has to know from end users is the Serial Id of the

Weather Station a user has received in the package, which is labeled on the product. Based on the Serial Id 'Building Monitor' can connect a customer with a specific Weather Station and its modules.

10.2.2 Modules

Netatmo Weather Station is initially delivered with two modules. One module can be installed on the outside to measure outdoor climate. The other module is the main module and serves as indoor module. It is possible to purchase up to 3 more modules, which can be used to monitor additional rooms.

All additional modules have a wireless communication with the main module and are battery powered. The main module is cable powered and acts as a central access point for the other modules. It also is responsible for uploading the measured data onto servers from Netatmo via a previously established internet connection.

Not all modules measure the same physical quantities. The following table lists the physical quantities, which are measured by the different module types.

Module type	Physical Quantity	Unit of Measure
Main Module (indoor)	Temperature	°C
	Pressure	mbar
	Relative Humidity	%
	CO_2 Level	ppm
	Acoustic Comfort	dB
Additional Module (Indoor)	Temperature	°C
	Relative Humidity	%
	CO_2 Level	Ppm
Outdoor Module	Temperature	°C
	Relative Humidity	%

table 6 physical quantities and module types

10.2.3 Features currently not supported in the 'Building Monitor'

Netatmo provides anonymous access to measurement data of all the outdoor modules through a Public API, unless a user has explicitly opted out to participate.

It could be interesting to use this data in 'Building Monitor' as well, for example to do plausibilty checks with nearby stations or to get access to climate data prior to the installation date of one participant.

10.2.4 Known issues

Proper handling of monitoring equipment isn't easy. 'Building Monitor's' results and recommendations relies strongly on the assessment of the measured data. Hence it is very important that the raw data are measured as accurate as possible.

During the pathfinder phase we encountered some issues with the Netatmo Weather Station, which are addressed in the following sections.

10.2.4.1 Low Battery power

Since additional modules are battery powered, it is possible that they stop measuring, if the batteries are not changed in time. Therefor ‘Building Monitor’ should also constantly monitor the health status of the devices and notify users when the battery level of one module gets too low. Fortunately, it is possible to retrieve the battery level information for a module through the Netatmo API.

10.2.4.2 Module placement

The accuracy of the measured values depends strongly on a correct installation of one module. For example, if the outdoor module is placed directly on a sunny spot, the temperature measurements will be biased. Also putting an indoor module to close to a radiator may result in biased measurements.

In the current implementation of the ‘Building Monitor’ prototype this issue has not yet been addressed. It would be necessary to do plausibility checks on the measured data from time to time. For example this could be resolved by comparing the measured outdoor temperatures with results from nearby stations. These comparisons could be retrieved through Netamo’s Public API, but theoretically also from any other public weather API. Users could then be notified about this issue and could be fed with best practice advices for the placement of the module.

10.3 Netatmo DataProvider

To support the Netatmo Weather Station a hardware specific *NetatmoDataProvider* was implemented in the prototype along with a supporting programming library to handle the communication with the Netatmo API.

This DataProvider supports

- the collection of measurements for a single meter
- the collection of the health status, i.e. battery status of all installed modules
- the retrieval of further information about the installed modules, like the geographic location and module names
- an experimental utilization of the public weather data API, which allows anonymous access to other Weather Stations within a given geographical boundary.

The collection of measurements over the Netatmo API has some limits. It is only possible to retrieve 1024 values within one request. Further restriction only allows up to 50 requests every 10 seconds and maximal 500 request every hour.

These limitations might be problematic in the future, when 'Building Monitor' has to handle more than 500 devices within its poll interval (currently 15 minutes).

10.4 Implemented Processors

Since the Netatmo Weather Station is only capable to monitor climate data, processors shall be implemented, which estimate energy performance of the building based on this data. Space heating demand is an example for this.

Energy demand for Domestic Hot Water or Electricity has to relay on public available load profiles.

The following sub sections give a short overview of the Processors, which were tested in the prototype version.

10.4.1 Generic Processor

The generic processor basically does not change or operate on any of its input data. The purpose of such a processor is simply to pipe the measured input data directly into the result repositories, where it is being aggregated.

This is being helpful for measurement data, which is displayed for the user *as-is* and is being implemented for the dimensions

- *Indoor Temperature*
- *Outdoor Temperature*
- *Indoor Relative Humidity*
- *Outdoor Relative Humidity*
- *Pressure*
- *CO_2-levels*

10.4.2 Adaptive Indoor Temperature Benchmark

This processor calculates on the basis of a series of outdoor temperature measurements a series of adaptive indoor temperature benchmarks.

Details on the implemented method can be found in section 3 *The computational model and display of information in 'Building Monitor'.*

Space Heating Demand

This processor simulates space-heating consumption on the basis of indoor and outdoor temperature difference.

Details on the implemented method can be found in section 4.2 *Heating.*

Domestic Hot Water
This processor simulates the domestic hot water energy demand on the basis of load profiles for water usage for different heater classes.

Details on the implemented method can be found in section 4.3 *Domestic Hot Water (DHW).*

Electricity
This processing module simulates the demand for electricity on the basis of load profiles for electricity.

Details on the implemented method can be found in section 4.4 *Electricity – domestic electricity use.*

11 Screen Design

Concerning the usability of a frontend of 'Building Monitor' a first approach has been designed during the development of the prototype.
As 'Building Monitor' is planned to be an online-based tool, in these days it would be most helpful to develop the interface as an app. Hence, the screen design was exemplarily conceptualized for a smartphone. The practicability and the user's comprehensibility by intuition of the interface were the most important aspects.

The start screen directly shows the main information starting with general data e.g. weather, date and the time of the last measurement (as we work with 15-minute-intevals with the NetAtmo devices). An overview of – on the one hand the measurements of CO_2-concentration, temperature and humidity and on the other hand the calculated (and partly extrapolated) energy data – is graphically displayed like a speedometer. The idea is to generate a playful dealing with the system.
The target of this display is to address the user directly with information about his own environment and show him by using different signal colors (red for "*bad*" and blue for "*good*") the status of his comfort. Some smart advices or alerts (e.g. "*CO_2-concentration too high – please open a window*") could help the user to interact with the system and optimize his situation.

The user can reach the expert view with detailed statistics of the different measurements via a simple scroll down. According to his specific concern and knowledge the user can scale the graphs from a yearly view stepwise (monthly, weekly, daily) to a presentation per hour. As a consequence the data will be more comprehensible and optimizations can be reconstructed on the display.

figure 23 a. start screen of 'Building Monitor' app
b. expert view of 'Building Monitor' app

TESTPHASE

12 Pilot Project // Montfoort houses

As a test case for ‘Building Monitor’ 92 terrace houses in the Dutch town of Montfoort were used. The houses built in the 1970s have undergone a major energy renovation in 2013, decreasing the energy consumption and increasing the comfort and living conditions. The renovation was conducted by the owner GroenWest in collaboration with the Velux Group.
All 92 houses were renovated to the energy label A, with ten of them being renovated according to the Active House standard[46]. The ten houses were equipped with passive and active systems to reduce the energy consumption further.

12.1 Description of the renovated houses

The first steps in reducing the energy consumption were passive means reducing the transmission heat loss from walls and windows. The insulation level of the original houses were improved by approximately 80% by replacing and adding insulation material in the walls, floor and roof. All windows were replaced reducing the heat transmission without reducing the daylight quality.
In each of the ten Active houses energy is produced with a 21m^2 photovoltaic system and 5,6m^2 thermal solar collector. The heating and hot water production inside the house is performed by a heat pump. The combination of photovoltaic modules, solar thermal collectors and heat pumps gives a calculated yearly primary energy performance of -14,8 kWh/m^2, which means that the houses produce more energy than they consumed. Studies of the impact of the user behavior have in many cases proven a difference between the calculated energy performance and the actual energy performance. GroenWest and Velux have therefor started a test period, aimed to verify the calculated energy performance. It wasn’t possible to find the expected energy consumption for the Label A houses.
In the Label A houses the heating and domestic hot water was produced with gas. In the Active Houses, heating and domestic hot water was produced by the heat pump.

12.2 Energy and indoor environmental metering

To quantify the effects of the renovation and comprehensive metering systems were installed in five of the Label A renovated houses and in all ten Active Houses.
In five of the Label A houses and in the Active houses smart meters were installed to monitor the electricity consumption. In the Active houses this meant that the total energy consumption was recorded through the smart meter. In the Label A houses the total energy consumption was a combination of the electricity and gas meter readings.

[46] See www.activehouse.info for more information on the active house standard

For a detailed survey of the energy consumption, one of the ten Active Houses was equipped with additional metering, enabling recoding of the combined water consumption, hot water, lighting, certain plug loads (washing machine, dryer, dishwasher, refrigerator, and freezer) and room by room consumption.
To monitor the indoor environment a measuring system was deployed in the 15 houses. The system measured the indoor and outdoor temperature [°C], indoor and outdoor relative humidity [%], indoor CO_2 concentration [ppm] as a measure for air quality, and indoor sound pressure [db].

13 Testing system validation

To test the collection and the computational process, it could be achieved to get access to measurements of the Montfoort houses. Montfoort utilized 18 Netatmo Weather Stations to measure the climate in 18 houses. Each house had 3 hardware modules installed: two in the inside and one outside to measure indoor and outdoor climate.

With the help of the Netatmo team, these devices could be made accessible for the 'Building Monitor' prototype through Netatmo's Partner API.

From the 18 devices 15 could effectively be used in the tests. Round about 8 million measurements were retrieved through the collector for 135 meters in total starting from 1. July 2015 until 3. March 2016. It was decided to focus on the data of the second half of the year 2015.

Unfortunately, not all devices send complete data within that time frame. Health status of the devices showed that they had issues with battery power, which has fragmented the measurement series over time.

The following tables show the measurement count for indoor and outdoor temperature for the test houses (AH-3 - AH-9, SR1 – SR7) in the observed period.

HOUSE	Jul-15	Aug-15	Sep-15	Oct-15	Nov-15	Dec-15
AH-3	17611	17701	17063	17702	17126	17648
AH-4	12196	3986	2088			
AH-5	17612	17670	17093	17690	17098	17672
AH-6	17490	17615	17091	17723	17105	10755
AH-7	17392	17756	17170	17764	17131	17702
AH-8	17655	17687	17172	17755	17143	17896
AH-9	17326	17705	15281	16508	17133	17402
AH-10	17813	17865	17265	17848	17226	17783
SR-1	17654	17690	17063	17740	17089	17641
SR-2	12101	17808	17285	17893	17290	17837
SR-3	13466	17635	17121	17382	17143	17709
SR-4	17738	17794	17111	17712	17126	17763
SR-5	17603	17654	17101	17707	17114	17719
SR-6	17607	17676	17102	17746	17129	17702
SR-7	17627	17699	17124	17554	17144	17593

complete
incomplete

table 7 Indoor Temperature: number of measurements per month and house

OUTDOOR	Jul-15	Aug-15	Sep-15	Oct-15	Nov-15	Dec-15
AH-3	8810	8849	8557	8850	6031	
AH-4	5744					
AH-5	8791	8823	8537	8844	8084	1336
AH-6	8826	8846	8557	8863	8566	5393
AH-7	8683	8707	8450	8863	8546	8830
AH-8			50			353
AH-9	8658	8853	5873	1230	3445	
AH-10	8817	1312				
SR-1	8807	8847	8511	8868	8303	8729
SR-2	7655	8919	8635	8943	8639	8916
SR-3	8831	8835	8562	8697	8554	8845
SR-4	6262					
SR-5	8757	7329	8185	8647	8302	7694
SR-6	8818	8827	8507	8767	8552	8829
SR-7	4676					

complete
incomplete

table 8 Outdoor Temperature: number of measurements per month and house

In summary only 3 houses had complete data within the time period and at least 6 houses could contribute with partial data in the tests that rely on indoor and outdoor temperature.

IN+OUTDOOR	Jul-15	Aug-15	Sep-15	Oct-15	Nov-15	Dec-15
AH-3						
AH-5						
AH-6						
AH-7						
SR-1						
SR-2						
SR-3						
SR-5						
SR-6						

Partial
Complete

table 9 Indoor and Outdoor Temperature

13.1 Validation of computational model

The recording of the energy consumption in the 15 houses started in July 2015 and was ongoing in March 2016. Preliminary results has been obtained by Velux A/S, but were treated as confidential until the final results were collected and analyzed. The validation of the computational model of ‘Building Monitor’ was performed by comparing the measurements and the calculated energy consumptions. Due to the confidentiality only the difference between the two was possible.

The computational model is based on the user to input the energy consumption for heating from the latest heating bill, from this the energy consumption per heating degree day is calculated and is used to calculate the real time energy consumption.

In the test case the annual energy consumption was unfortunately unknown/inaccessible, the energy consumption per heating degree (Q_HDD_Space_Heating) was estimated by the total energy consumption for six months (July – December 2015). Further assumptions for the houses were made according to the following:

In Label A houses, to subtract the DHW consumption from the heating consumption, the monthly average consumption was calculated based on the average consumption in July and August, which then was subtracted from the total gas consumption. By this assumption it was assumed that heating wasn’t used in July or August 2015. The assumption means that 79% of the gas consumption was used for heating and 21% for DHW.

In the Active houses, all energy consumed was electricity based. Estimating the energy consumption for heating and DHW was therefor based on the detailed measurements performed in one of the Active houses. The detailed measurements showed a consumption for heating and DHW of 90% of the total consumption from July 2015 through December 2015. The distribution between heating and DHW was the same as in the Label A houses.

13.2 Difference between measured and calculated

The differences between the measured and the calculated energy consumption are presented in figure 24.

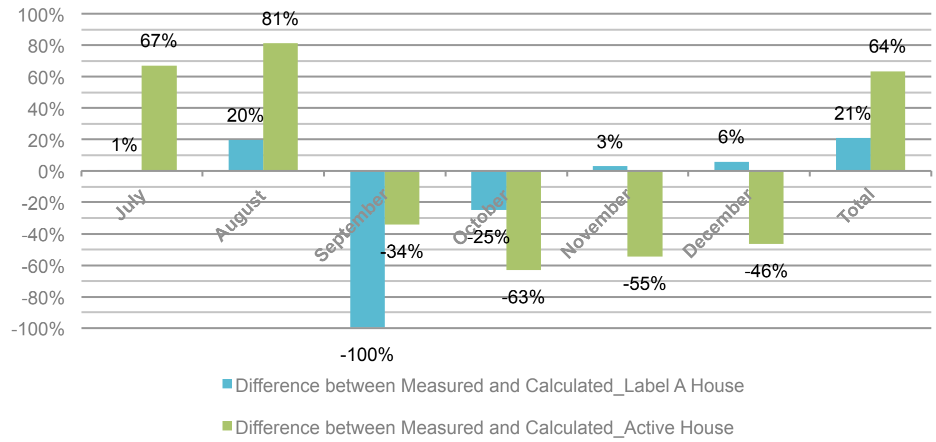


figure 24 Difference between the calculated and measured energy consumption

The calculated energy consumption differs from the measured consumption with 3% and 6% in November and December, respectively. A difference so small, that it seems acceptable when used in an actual household situation.
During the heating season heating must be used throughout the day to maintain comfortable temperatures. However, in the transition months of September and October heating isn't necessarily always needed to maintain a comfortable thermal environment. The relatively low differences in November and December was seen as an positive validation of the computational model and it is therefor considered plausible that the differences in September and October were due to the way the occupants actually consumed heating. This result shows that determining whether heating is in use or not, perhaps should be reconsidered in 'Building Monitor'.
In the Active Houses differences between 34% and 81% throughout the six months were seen. The main reason for the difference between the measured and calculated consumption, is the uncertainties in heating consumption and the calculation of *Q_HDD_Space_Heating.* The uncertainties originate from the detailed measurements performed in one Active House, from which it was very unclear what was used by the heat pump and thereby for heating.
All in all the validation showed that the computational model will compute heating consumption with a low difference between the calculated and the actual energy consumption in the heating season. However, the computational model should be used with care in the transition months.

13.2.1 Excel validation

To further validate the computational model a calculation procedure was built using Microsoft Excel. By using an assumed energy consumption for Active House 7 and the indoor and outdoor temperature profiles from this house, the energy per heating degree day and number of heating degree days were calculated, in both Excel and 'Building Monitor'. A comparison of the results showed a difference of 0,3kWh/°C HDD, which could be explained by the number of heating degree days – 'Building Monitor' counted two days less because of the outdoor temperature, a feature which wasn't incorporated in the Excel calculation.

13.2.2 Using consumption from Building Performance Simulations

In the Active House evaluation the annual energy consumption was estimated using the building performance simulation tool Be10. A simulation tool developed to certify Danish buildings. The simulation tool assumes an indoor temperature of 20°C leaving no room for user behavior adaption, as described earlier. The energy consumption estimation was used in initial assessment of the difference between the measured and calculated. The assessment showed average difference of 81% and 77% for Label A and Active Houses, respectively. The differences showed that energy consumption estimated from building performance simulation should either not be used or should be estimated by simulation tools including a model that a low for a better incorporation of user behavior than a fixed indoor temperature does.

13.3 Conclusion

Due to the lack of information on the energy consumption in the houses in the test case, it was not possible to validate the initial user input method. However, a similar procedure was tested; showing a difference between the measured and the calculated heating consumption of 3% in November and 6% in December. The results showed that using the method for calculating the energy consumption in transition months were more difficult, because low outdoor temperatures in these months don't necessarily mean that heating is consumed.

In the test of the Active Houses, high differences between the measured and the calculated energy consumption were found. The results showed the importance of the quality of the user input and that a focus of future work would be on determining the distribution factors.

The 'Building Monitor' computational model was further validated by comparison to an Excel calculation. The results showed that the calculation procedure of 'Building Monitor' is correct. This result supports the findings of the Montfoort validations, about the quality of the inputted energy consumption.

A test using energy consumptions from building performance simulations showed differences of 81% and 77% for Label A and Active Houses, indicating that simulation results should only be used if the simulation model includes occupational behavior models.

MARKETABILITY STUDIES

14 Market research

'Building Monitor' can be located within the smart home market. Smart home brands and products have received considerable interest following high-profile investments (e.g., Google's acquisition of Nest, the purchase of SmartThings by Samsung) and product launches (e.g., Apple's integration of its HomeKit platform into iOS) in recent months. A new wave of start-ups in smart home and adjacent markets (e.g., wearables) has likewise drawn media attention and continues to intrigue technology-minded consumers. Smart home and related concepts have also found their way onto political agendas. The European Union has begun the rollout of smart meters in its member states, expecting to replace 200 million traditional electricity meters with smart meters by 2020.[47]
However, despite the term's increasingly common use, the ideas and market spaces behind "smart home" remain difficult to grasp for consumers and organizations alike.[48]

14.1 Defining the smart home market

Smart home products are broadly understood to contribute to the users' living comfort and quality of life.[49] However, the purposes, value propositions, and technical implementations of products gathered under the label varies widely. At minimum, the market is thought to include the following segments:[50]

(1) home security
(2) home entertainment
(3) energy management and conservation
(4) ambient assistant living, health, and comfort

'Building Monitor''s value propositions correspond to multiple segments within the larger smart home market. The stated mission for the product is to optimise building performance with respect to both energy consumption (section 4) and occupants' well-being and health (section 6), eliminating existing conflicts between these objectives. While energy consumption is featured prominently within this proposal, consumers' need not share this priority.

[47] European Commission, 2014
[48] Icontrol networks, 2015
[49] Bitkom Fokusgruppe Connected Home, 2014
[50] adapted from Verband der Elektrotechnik, 2013

Prior to deciding upon a particular communication strategy, is it therefor not clear in which segment consumers will place the product[51].

From both a marketing and a technology perspective, the smart home market is closely tied to the emerging Internet of Things (IoT), from which it obtains some of its technological underpinnings and with which it shares the promise to create value from distributed, autonomous data collection and information sharing between devices. As IoT devices, smart home solutions are fundamentally characterized by the following abilities [52]:

a) collect and analyse data autonomously
b) execute actions autonomously
c) connect with other smart home devices, allowing for the integration of multiple devices into unified systems
d) connect with mobile devices, allowing for remote access and notifications

‘Building Monitor’ does not implement all of the functional characteristics associated with IoT devices. In particular, it does not implement automation, but instead offers smart, customized recommendations for action. The results of a Nielsen consumer survey (Figure 25) on IoT and “smart” devices suggest that ‘Building Monitor’ nonetheless matches the profile of a “smart” product.[53] Nielsen investigated consumers’ demand for various functional characteristics associated with “smart” or IoT products. Perhaps surprisingly, recommendations were requested by a greater percentage of consumers than were automatic actions. Consumers furthermore appear to assign considerable importance to devices’ ability to learn and adapt. Customization, autonomous learning, and adaptation to the particular situation and preferences of its users are core features of ‘Building Monitor’, implemented through the product’s simulation and prediction module.

[51] Note, for instance, that Netatmo’s weather station, the device at the core of ‘Building Monitor’, monitors environmental variables rather than energy consumption. As a result, its environmental sensor data may be updated at a higher frequency than the household’s electricity consumption data provided by the software, unless a real-time electricity monitor is added to the package. Such factors may cause consumers to categorize ‘Building Monitor’ as a well-being proposition, contingent on the seller’s communication strategy. We suggest that this ambiguity is advantageous rather than worrisome and will return to it in the following chapter.
[52] adapted from Bitkom, 2014
[53] The Nielsen Company, 2014

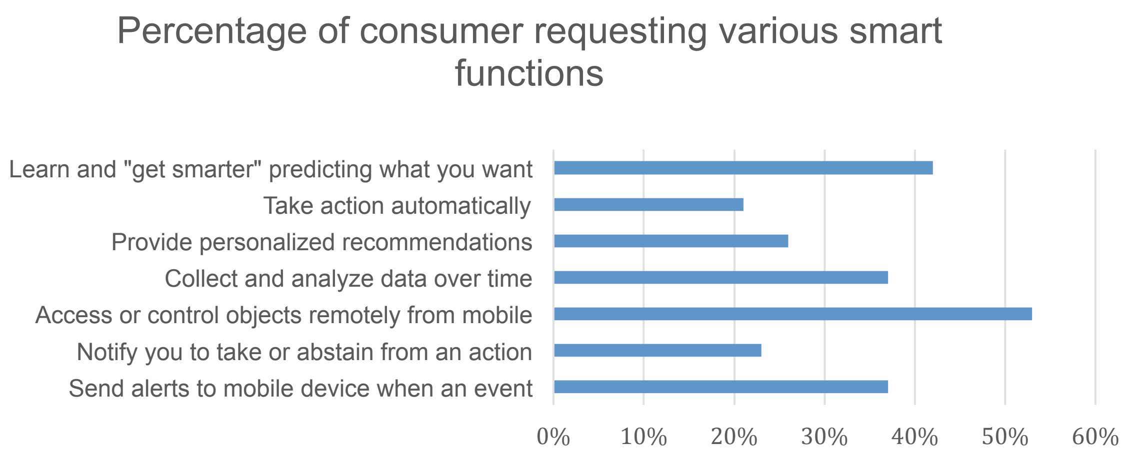


Figure 25: Smart features requested by consumers

14.2 Global market outlook

Smart home devices and services are recognized as a quickly growing market with considerable potential for further growth. Strategy Analytics expect smart home revenue from products and services in Europe to grow from 8 billion US dollars in 2014 to 17 billion dollars in 2019[54]. Revenue in Germany alone is predicted to expand from 2 billion US dollars in 2014 to 3.7 billion in 2019. Deloitte predicts revenue to grow from 3 billion Euro in 2015 to approximately 4 billion in 2017. Figure 26 provides an overview of market size predictions by different institutions.
Considering the prospects for individual market segments, yearly growth rates exceeding 30% are expected for all segments (see Figure 28). In the light of the data cited here, it may appear curious that according to a 2013 study by Deloitte, smart energy revenue is expected to stagnate between 2015 and 2017[55]. However, the segment definition used in that study deviates from other studies in the field, making comparison somewhat difficult. It is also noteworthy that the same study predicts a 60% increase in smart home health care revenue during the same period. We have included by-segment predictions for key European markets Germany and France (Figure 28).

[54] Strategy Analytics, 2014
[55] Deloitte, 2013

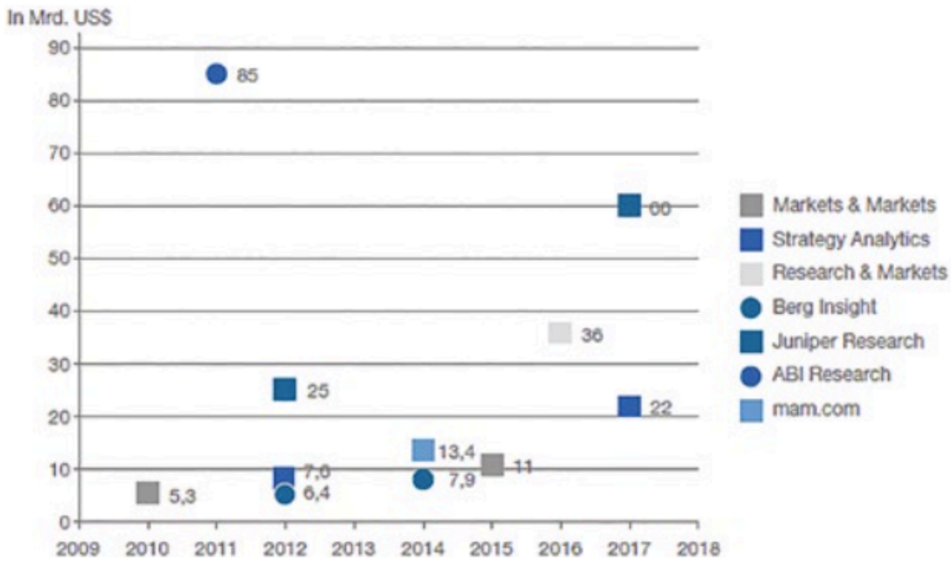


Figure 26: Smart home market size predictions

Nonetheless, the global smart home market is still in its infancy and the installed base remains small. In 2015, only approximately 300,000 households in Germany owned smart home equipment. This figure is expected to grow to 2.4 million households in 2020. In the United States, who lead the worldwide adoption of the technology, the penetration rate in 2015 was significantly higher at 4.6 million households, a number expected to rise to 24.5 million in 2020[56]. Worldwide, Strategy Analytics (2014) places the proportion of households owning at least one smart home system at 6% in 2015 and predicts the figure to grow to 12% by 2019.

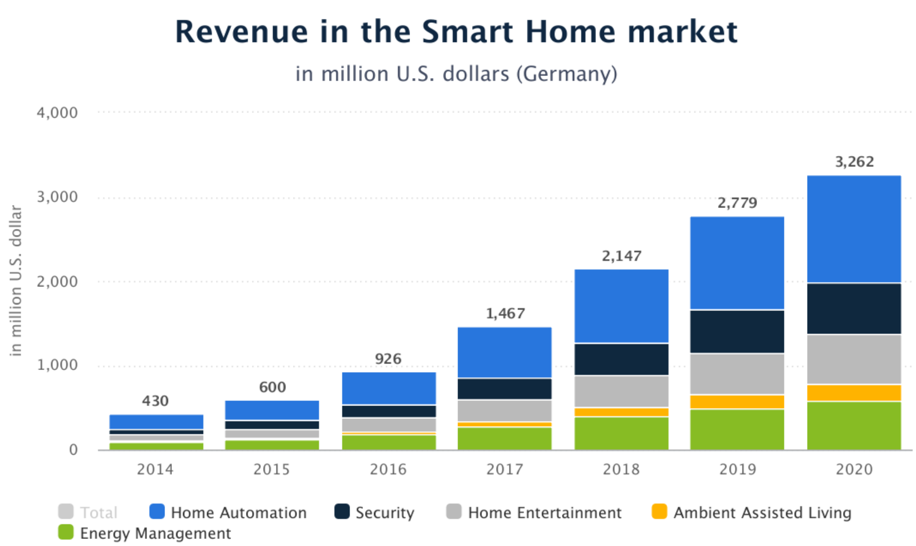


Figure 27: Smart home revenue in Germany

[56] Statista, 2015; Digital Market Outlook

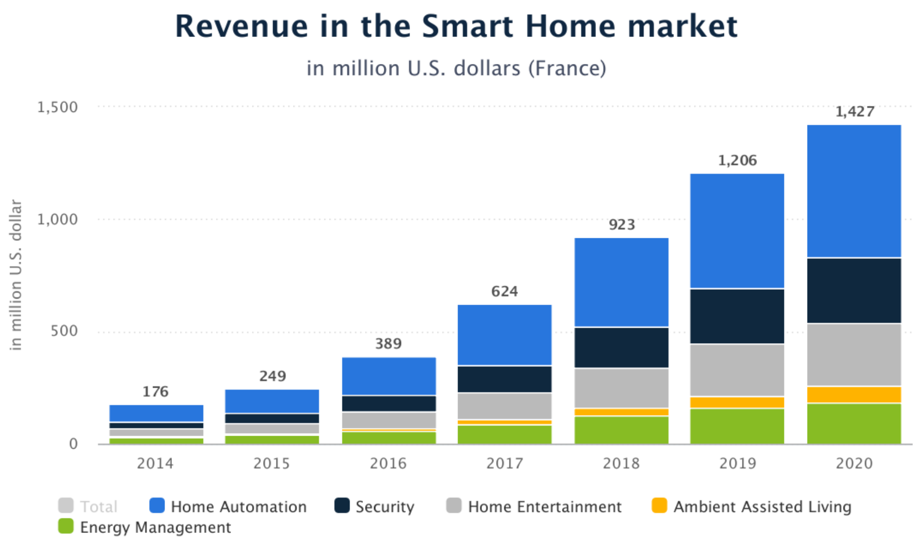


Figure 28: Smart home revenue in France

14.3 Energy management outlook

Energy efficiency and conservation has been an early frontrunner among smart home segments and is expected to show strong growth in the future. We have included predictions for the growth of this segment in France and Germany (figures 29 and 30) and primarily discuss consumers' motivations in the following.

In a 2011 survey, Capgemini found that among consumers interested in smart home, energy efficiency solutions were perceived as the most important smart home domain. Experts, however, favoured entertainment as the most important domain.[57] But more recent studies suggest that that smart energy solutions might indeed be the bigger topic. Among German consumers surveyed as part of the DFH Trendbarometer Nachhaltigkeit, 84% of respondents agreed that functions to better monitor their energy consumption through smart home solutions would be useful to them.[58] In the 2014 iteration of the same study, 96% of respondents agreed that reducing costs by improving energy efficiency would be important to them when constructing a home.[59] A Deloitte study from 2015 estimates German consumers' desire to save money to be somewhat less important, with 31% of interested consumers naming it as a key motive behind their interest in smart home. Comfort (47%) and security (43%) claimed the top spots, with 70% of the youngest consumers (24 years and younger) citing comfort as the main driver of their interest. The desire to save money on energy bills is also contributing to interest in the United States. Nielsen reported in 2014 that 65% of the American consumers they surveyed cited saving money as their top reason to adopt IoT solutions. Nielsen also noted that the desire to save money was found to drive preferences across a considerable range of product categories.

In contrast, Icontrol reported in 2015 security as the smart domain receiving the strongest interest from consumers in North America, with 90% of consumers excited about it. But in second place where again energy monitoring and efficiency, with 70% of respondents reporting excitement. This figure may be contrasted with 47% of respondents who stated that they were excited about helping the environment by increasing their energy efficiency. The gap suggests that financial motives play a strong role in the pursuit of energy efficiency, in line with previously cited studies.

[57] Capgemini, 2011
[58] DFH, 2012
[59] DFH, 2014

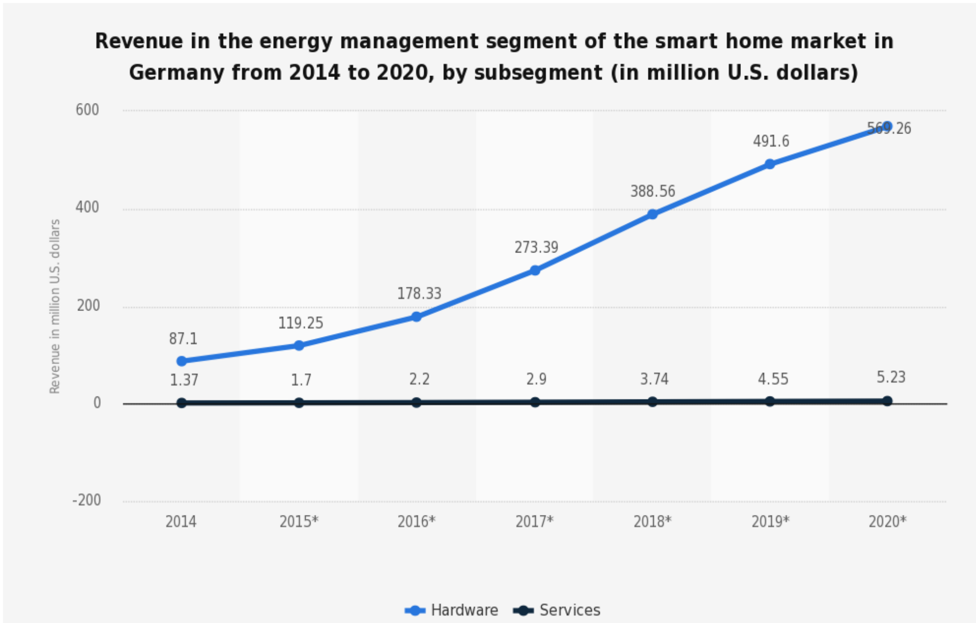


Figure 29: Energy management revenue predictions for Germany

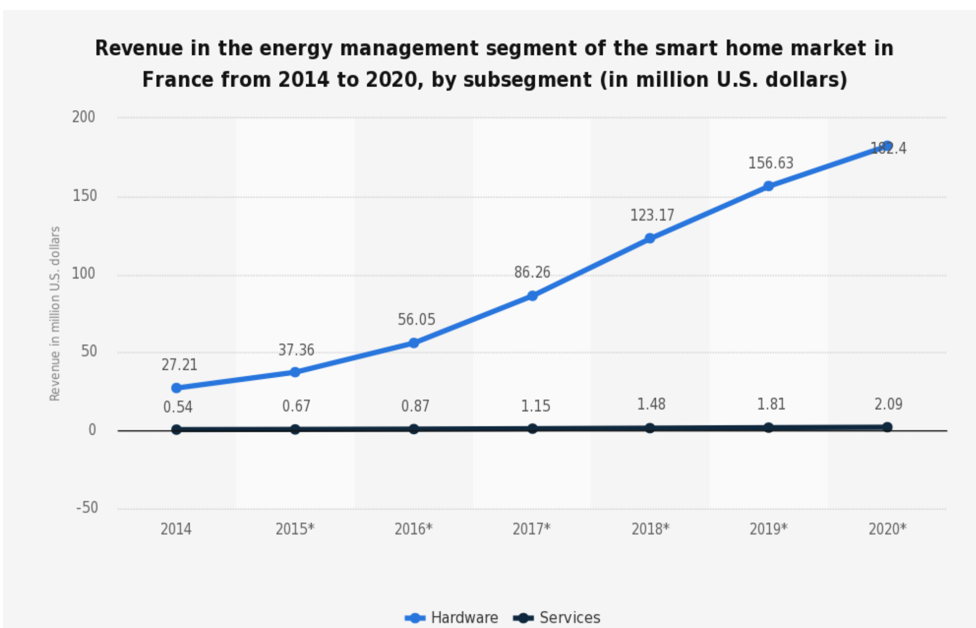


Figure 30: Energy management revenue predictions for France

More studies support the importance of savings and efficiency concerns. The Internet of Things Consortium reported that 60% of consumers surveyed find security and energy efficiency the most attractive advantages offered by smart home solutions, with 44% looking to save money and 37% seeking to upgrade their home entertainment experience.[60]

Energy-efficient and automatic heating stands out as a potential benefit with consumers. Icontrol respondents also showed strong interest in self-adjusting thermostats, with 72% stating they desired owning such a device. When respondents were asked which products they would consider purchasing within the next 12 months, connected home cameras (security) and connected thermostats (comfort/energy) emerged as favourites, with 37% of respondents considering a purchase. A study among German consumers (Deloitte 2015) yielded similar results, with 38% of respondents interested in security systems and heating and thermostat systems in second place at 34%. A KRC & GSMA survey among consumers in the United States, the United Kingdom, Germany, and Japan showed that 25% of respondents expected to be using a smart energy meter within the next five years. The device category most respondents expected to be using were smart appliances, at 37%.[61]

On a cautionary note, it is somewhat unclear how easily interest in energy efficiency solutions can be translated into demand. As the European Union's CA EED point out, energy bills usually consume a small part of available income and occur only periodically. It is also noted that personal savings from smart metering may be too low to generate and maintain engagement and that monitoring and managing energy consumption may ultimately be found unappealing.[62] However, these concerns are not immediately borne out by surveys among smart home users. A Statista survey among German users of smart home solutions revealed that 41% of respondents agreed that they were saving energy because of their smart home installation, second only to perceived improvements in comfort (43%).[63] Only 3% felt that they had had no benefits from their smart home solution. KRC & GSMA reported that 72% of those who own a smart energy device said that they were saving money. The same research also found that 90% of early adopters would consider purchasing a connected system if it could save them approximately 300€ or more per year.

While expectations about the smart home market are generally positive, some analysts have warned of a delayed breakthrough and consumer disillusionment in the short term. In its 2015 Hype Cycle for Emerging Technologies, Gartner suggests that the Internet of Things is currently passing through a phase of inflated expectations and predicts that the technology will not achieve a performance that aligns with expectations before another 5-10 years have passed.[64] A similar sentiment is found among at least some consumers. According to the Bitkom survey,[65] German consumers expect a market

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[60] Internet of Things Consortium, 2014
[61] KRC Research & GSMA, 2015
[62] European Union Concerted Action Energy Efficiency Directive, 2015
[63] Statista, 2015: Meinung zu Smart-Meter-Anwendungen von Nutzern in Deutschland
[64] Gartner, 2015
[65] Bitkom, 2014

breakthrough to occur around the years 2019-2024. PricewaterhouseCoopers suggests that the market will enter into its defining growth phase in 2017 but approach maturity and saturation only by 2030.[66]

In 2015, Argus Insights reported that the number of consumer reviews written about smart home products from all segments was strongly decreasing.[67] Based on these data, they inferred that earlier growth of the smart home market may currently be reverted. They suggest that a first wave of early adopters may already have been exhausted, with current potential buyers unsure what device they might want and which benefits they might gain. A recent report by Icontrol[68] likewise remarked that smart home remains an either ambiguous or empty concept for many consumers and that some value propositions are unconvincing.[69]

While stated interest in smart home is generally high among survey respondents, Argus Insights' analysis of social media conversations (2015) indicates that home automation topics receive far less interest than, for instance, the wearables market. Such data suggest that the possibility of bias in the results of traditional direct surveys must at least be considered. Especially where smart home is paired with topics such as energy conservation, demand artefacts (e.g., respondents giving socially desirable answers) may exaggerate positive results. However, the fact that consumers consistently focus on monetary savings as a key motive behind their smart home interest suggests that such inflation is not severe.

14.4 Further insights

Word-of-mouth is important for smart home adoption.
Smart home appears to be partly a social phenomenon. Icontrol[70] reports that 50% of American consumers claim to be excited about smart home, but among those who know someone who owns smart home equipment, 83% find themselves excited. Beyond excitement, the same study finds that purchase intentions for a variety of products nearly double for respondents who knew someone with smart home equipment. Consumers explicitly report that word-of-mouth is important to them (e.g., 37% versus 69% interested in a connected thermostat).

Privacy is an issue for both American and European consumers.
53% of American consumers find themselves worried that their data may be shared without their approval, and 51% are concerned about their smart devices being hacked.[71] A study by several IoTC members even found 66% of their respondents express privacy concerns.[72] For German consumers, privacy concerns are the main

[66] PricewaterhouseCoopers, 2015
[67] Argus Insights, 2015
[68] Icontrol, 2015
[69] see also Nielsen, 2014
[70] Icontrol, 2015
[71] Nielsen, 2014
[72] IoTC, 2014

disadvantage they associate with smart meters, cited by 27% of respondents.[73] Similar concerns prevail with regard to smart home, where consumers see the possibility of abuse (71% of respondents) more critically than costs (61%) and other concerns.[74] Crucially, privacy concerns seem to translate into market choices, as 66% of German consumers state that they would prefer a German smart home provider over a non-German one.[75]

Smart home interests vary with consumer age and role.
While younger consumers seek to gain comfort, older consumers are more excited about security.[76] Interest in energy efficiency is very high among both young and old, though older consumers are slightly more excited about this prospect.
Privacy concerns also vary with age. Among German consumers aged 19-24, 65 would generally be willing to share their smart home data. This figure drops to just 24% among those aged 65 and older.[77]

Ease may be an underestimated issue.
Argus Insights[78] noted that consumers' experience frustration in setting up and connecting their smart devices. This notion is indirectly supported by a survey among German smart home users, in which only 19% of respondents agreed that installing their smart home device had been an easy experience.[79] In addition, it must be noted that many current smart home users may fit the description of tech-savvy early adopters. Installation procedures and interaction paradigms which may have been accepted by this generation of buyers may not be tolerated by the next.

Smart home devices provide added value, but manufacturers must keep innovating.
Icontrol[80] have noted that at this point many "smart" products offer little incremental benefit over their traditional counterparts, or lack incentives that would keep consumers engaged with their purchases. However, a Deloitte study among German consumers found that merely 23% of those not interested in smart home cited no added value as a reason for their lack of interest, compared to 44% finding smart home devices too expensive. Nielsen[81] report that 41% of consumers find the majority of smart home devices unimpressive in terms of added value. They also note that consumers are becoming less impressed with simple smart features (e.g., recurring recommendations), but will be enticed by advanced smart capabilities on products.

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[73] Forsa, 2010
[74] TFM, 2015
[75] Deloitte, 2015
[76] Icontrol, 2015
[77] Deloitte, 2015
[78] Argus Insights, 2015
[79] Statista, 2015
[80] Icontrol, 2015
[81] Nielsen, 2014

15 Consumer expectations

In order to validate and extend our understanding of prospective customers' expectations, original market research will need to be conducted. Broadly speaking, the following questions are potentially of interest:

(1) Are consumers actively thinking about the issues that 'Building Monitor' seeks to address? What are the relative weights they assign to goal dimensions such as energy saving, room climate, and general well-being?
(2) How do consumers perceive the product features that will potentially be implemented in 'Building Monitor'? What features must be implemented to avoid dissatisfaction and what negative qualities must be avoided?
(3) How much are consumers willing to pay for the product? How does this change depending on the competitive framing, e.g., when certain competitors become highly visible in the market?
(4) Which discrete components, e.g., sensors, should be bundled with the core product, and how many of each item should be included?

At the current stage of the project, the information needs of management are mostly covered by questions about product perception (2) and willingness to pay (3).

15.1 Product features

Consumer knowledge about smart home products remains relatively low. It therefor cannot be expected that consumers will be immediately aware which technical features constitute the technical baseline in a product category, which features a product is likely to possess, which features offer the greatest utility to them, or which limitations are the norm. Given these circumstances, it is proposed to employ the Kano approach to investigate consumers' technical product requirements. The Kano model[82] is a method to identify the relationship between the degree to which a feature is implemented in a product and the satisfaction that results for the consumer. The Kano model is considered to be well suited to extract expectations which consumers would not articulate unprompted or which they would find difficult to describe.[83] Furthermore, through the use of both negative (dysfunctional) and positive (functional) questions, the Kano approach enables the market researcher to study the impact of both negative and positive product qualities on consumer satisfaction.

[82] Kano, Noriako, 1984
[83] Matzler, Kurt; Hinterhuber, Hans; Bailom, Franz; Sauerwein, Elmar, 1996

Ultimately, the Kano approach allows the researcher to distinguish five types of product dimensions:

Type	Consumer satisfaction
Must-be Quality	Dissatisfied if absent, neutral if present
One-dimensional Quality	Increases linearly with the degree to which feature is present
Attractive Quality	Neutral if absent, highly satisfied if present
Indifferent Quality	Neutral if present or absent
Reverse Quality	Dissatisfied if present, satisfied if absent

Table 10: Product quality types according to the Kano approach

We noted earlier that uncertainty persists among consumers and organizations about the added value offered by smart home products. The classification of features according to the Kano scheme renders the value added by potential product features transparent.[84] Furthermore, it allows management to reduce costs and increase revenue by forgoing features about which consumers are indifferent, and focusing on attractive qualities.

The ability to identify reverse qualities is crucial in deciding upon the appropriate level of complexity for 'Building Monitor'. As has been discussed in earlier chapters, 'Building Monitor' is able to provide a wealth of information and recommendations to the user. However, the more information one ambitions to provide through the software, the more information must be fed into the system. Considering the emphasis placed on automatic data collection and processing in the IoT and smart markets, any manual input of information by the user must be considered a potential reverse quality. The Kano model helps to resolve the complexity conflict by providing insights on the perceived usefulness of specific recommendations and the perceived costliness of inputting the information that these recommendations require.

Other reverse qualities may be the result of consumers' implicit understanding of 'Building Monitor''s product category membership. Because the Smart Home market is currently in an emerging state and consumer expertise is limited, the subjective classification of the product is not clear. If 'Building Monitor' is implicitly considered similar to integrated smart home solutions, the relative lack of automation and control in 'Building Monitor' might be received with disappointment. If 'Building Monitor' is categorized alongside other non-integrated smart appliances, such limitations should

[84] The Kano approach may not be ideally suited to assess the relative attractiveness of different levels for the same attribute (e.g., electricity consumption updates at 0.5, 1, 2, or 3 hour intervals). This drawback is of little importance in the present context, as nearly all of the features under consideration here come in only two levels, namely present or absent.

not be perceived as deficiencies. The Kano approach is able to implicitly inform the researcher about perceived category membership.

Table 11 shows a set of examples of potential reverse qualities.

Category	**Feature**
Data input	Well-being [periodically][85]
Data input	Shower frequency and duration [once]
Data input	Energy bill [periodically]
Data input	Electric devices present in the household [once]
Data input	Usage frequency of electric devices [once]
Data input	Floor area [once]
Data input	Occupancy [once]
Data input	Presence by log-in [event]
Usability	Interaction outside of app required (e.g., uploads to web interface)
Installation	Registering device with manufacturer
Absent feature	Integration of thermostat data
Absent feature	Integration of smart meter data
Privacy	*Rephrase remote access features as privacy concerns*

Table 11: Examples of reverse qualities

Implementation of the Kano model is relatively inexpensive and requires comparatively limited methodological expertise. It yields valid results with small sample sizes of 20-30 subjects per homogenous consumer segment.[86] We aim to exploit this economy by surveying several consumer segments, as shown in Table 12. The design shown has been compacted, combining segmentation variables (e.g., ownership and household size) and cutting cases from each variable. There remain a total of 18 segments (3 x 3 x 2) from which respondents may be recruited. Assuming 30 participants per segment, this yields 540 participants. At this size, the study can be efficiently replicated for multiple countries, if desired.

[85] The provision of well-being data cannot a priori be said to constitute a reverse quality. It is conceivable that consumers may wish to provide such data at a high frequency, as they will be aware that this means having denser data at their disposal in the future.
[86] Griffin, A.; Hauser, J. R., 1993

Segmentation variable	Value
Age	25-39
Age	40-54
Age	55+
Knowledge	Medium, no smart home
Knowledge	High, no smart home
Household	Renting or owning apartment, 1 person
Household	Renting or owning apartment, 2+ persons
Household	Owning house, 2+ persons

Table 12: Segmentation example

15.2 Willingness to pay

Deciding upon an appropriate price for 'Building Monitor' is a key strategic challenge. Pricing decisions generally require information about: (1) the cost of the product, (2) the prices set by competitors, and (3) consumers' perceptions of the product's utility. Competing alternatives and utility perceptions enter into consumers' measurable willingness to pay.

Momentarily neglecting fixed costs, a lower bound is placed on the price of 'Building Monitor' by the cost at which its component devices can be procured. Beyond this lower bound, however, the absence of highly similar competitors diminishes the usefulness of observing market prices. It therefor appears necessary to conduct original research on consumers' willingness to pay for 'Building Monitor' to establish an upper price bound. Willingness to pay may be measured directly or indirectly. Direct measurements have been found to yield clearly inferior data under specific circumstances but tend to provide useful approximations in most scenarios.[87] Alternatives with a potentially higher external validity (e.g., incentivized WTP tasks, conjoint analysis), are not efficient in the given context because of higher costs, higher technical requirements, and the necessity to provide prototypes or a product that may be transferred to the subject as part of the WTP task. It is therefor proposed to apply a direct approach to measuring willingness to pay as a first step. The following established questions are to be posed in the order given:

[87] Direct methods tend to yield WTP estimates that are lower than consumers' true WTP. A common concern is that consumer may state a WTP that is too low for fear of enticing manufacturers to raise their prices. Such concerns do not appear to apply in the present context.

1. *How much would you be willing to pay for this product?*
2. *What would you consider a fair price for this product?*
3. *Would you consider purchasing this or a similar product?*

At the current time, there remains considerable uncertainty with respect to the competitive environment surrounding ‘Building Monitor’ at its launch. In particular, it is unclear which competing alternatives ‘Building Monitor’ will be compared against by consumers. Owing to this uncertainty, a multi-scenario approach to measuring WTP is proposed, where ‘Building Monitor’ is presented alongside various potential competitors. Table 14 lists prototypical scenarios to be considered. The current market price is to be displayed for the competing product.

Focal product	Competing product
‘Building Monitor’	None
‘Building Monitor’	Netatmo weather station[88]
‘Building Monitor’	Smart energy competitor
‘Building Monitor’	Smart home automation solution (optional)

Table 13: Competitive scenarios for WTP measurements

Optionally, a simple survey may be conducted to obtain consumers’ awareness of each competitors and extract their propensity to conduct each comparison. Awareness of each competitor and propensity to compare against it can then be used to weight the results obtained from individual WTP studies.
The WTP studies are also informative with regard to the optimal communication and placement strategies of the selling organization. Communication and placement (e.g., distribution channel) decisions influence which comparisons consumers will be likely to conduct and thus shift the weight to be assigned to the competitive scenarios outlined above.

As noted earlier in this chapter, ‘Building Monitor’ can be characterized as a product bundle. A variety of additional smart devices could potentially be added to the bundle to improve accuracy and increase consumers’ engagement with the system. Additional sensors would extend the set of environmental variables that can be tracked. For instance, Samsung’s *SmartSense Multi Sensor* detects whether a window or door is open or closed, while also being able to detect changes in temperature and movement. The *Smappee* smart meter monitors electricity consumption either at an individual outlet or at the building’s main power input. Connected to a power main, the device is able to monitor both overall electricity consumption and consumption by individual devices in the household in real time. Devices measuring water consumption in real time, such as

[88] As interested consumers are likely to possess some knowledge of the smart home market in general and ‘Building Monitor’ in particular, it must be expected that they will be aware of the possibility of purchasing the netatmo weather station as a standalone device. In this scenario, the incremental features (and costs) of ‘Building Monitor’ may be considered a software or service purchase. Willingness-to-pay responses may differ considerably under this particular scenario.

FLUID, or devices measuring hot water consumption at specific outlets might likewise be added to the bundle. Adding any such component would alleviate the need to input water consumption data manually. Even the bundling of security equipment alongside the core system could potentially provide added value. Home camera systems such as netatmo's *Welcome* identify people entering and leaving a room or building. Including such a device would allow for highly customized recommendations based on the individual preferences of a room's current occupants and alleviate the need to manually provide information and occupancy or register one's presence.

The attractiveness of extended bundles is difficult to evaluate using the Kano model. Including additional components increases the bundle price and complicates the installation process. But the Kano model gives the best results when treating costs and benefits as independent, and is therefor not highly suitable for determining willingness to pay, in time or money, for a particular addition. In its stead we propose to use choice-based conjoint analysis to derive the optimal bundle configuration. During conjoint data collection, subjects are presented with sets of different product configurations and asked to choose between them. All product configurations are described on the same dimensions and state a price for the given product. Following data collection, the attractiveness of individual components and product features is extracted from subjects' choice behavior through statistical procedures. Conjoint tasks have relatively high predictive validity, as they tend to mirror real-world choice situations.[89] Furthermore, the inclusion of price information forces consumers to reflect on the utility they obtain from additional components which raise the price. Conjoint responses are also less affected by demand artifacts than direct approaches to measurement.

While we deem conjoint analysis appropriate for investigating possible bundle configurations, we do not intend to employ conjoint analysis to study consumers' perception of core technical features, but there favor the Kano approach. Conjoint analysis is not well suited to study product qualities that may be perceived negatively by at least some consumers. The method inherits the assumptions made by the statistical procedures it employs to extract utility estimates, and these assumptions may be violated in the aforementioned case.[90] Furthermore, conjoint analysis is difficult to apply in cases where a product is not easily decomposed into independent features.[91] The method is also heavily constrained with respect to the number of product dimensions and features that can be studied at once, rendering it more suitable for confirmative analyses at later stages of the product design process, when the product has been defined more clearly.

[89] Breidert, Christoph; Hahsler, Michael; Reutterer, Thomas, 2006
[90] This refers particularly to the assumption of normally distributed errors, and, relatedly, the possibility of the true distribution of perceived utilities being multimodal.
[91] This may appear equally true for the Kano model discussed earlier. However, the Kano model gives researchers more space to describe individual attributes and likewise allows subjects to engage more deeply with individual features. It is even possible to describe a different product context for each attribute studied, thus investigating the possibility of conditional attribute perceptions.

CONCLUSION

16 ‘Building Monitor’ as dynamic user interface

In ‘Building Monitor’ a model has been developed that is capable of bridging that gap by

- Prioritizing the importance of data and information
- Using computational model for the extrapolation of information based on external references and a minimum on internal measurements
- Modelling processes to substitute data which can not be measured in the system

The most important parameter to determine how the information is displayed and in how far the user has the possibility to optimize or reduce associate energy use by adapting the settings of the building or his behavior. It makes little sense to confront the user with information that he cannot influence. This might even be harmful to the success of the whole system. The success of ‘Building Monitor’ depends on the acceptance of the users. If they understand that the system will provide them with specific valuable information, they might continuously work with the system and change their behavior and comfort levels accordingly. If ‘Building Monitor’ generates a lot of information that they can do nothing about what so ever, they will abandon the system sooner or later.

Therefor, providing relevant and specific information that the user can relate to his own preferences and behavior is crucial.

A first prototypical version of ‘Building Monitor’ has been developed in a pathfinder project stage. A lot of research is still necessary to develop the prototype into a marketable product. Nevertheless the system covers the complete range of questions relevant for the energy consumption in the building and the well-being of the user. In the combination of the two aspects it is a unique and new approach that will be completed by the individualization of the user profiles in the system.

17 Outlook

The research and development indicates an interesting opportunity to re-invent a user interface for buildings. All existing systems focus on the technical problem of gathering information and displaying it in a way that makes sense from a technical point of view. But this technical point of view is neither effective nor appealing to people. Displaying temperatures, indoor climate data or energy consumption is interesting for scientists who work in this field, but the inhabitants of apartments do not care enough about this kind of knowledge to associate and adapt a specific behavior to those data.

Even if the inhabitants are interested in improving the comfort in their home or the building performance, the interaction between the displayed information and their actions is very abstract. ‘Building Monitor’ offers a chance to bridge this gap.

Technical devices that are effective in the communication with people are far more responsive and specific:

- Driving a car is a continuous interactive experience which some people even perceive as being pleasant (up to a certain point at least)
- A smart-phone is not only highly responsive but offers endless opportunities to be adapted to specific interested and tasks, the user might find useful

‘Building Monitor’ would need to implement the same level of interaction and ease of use like the above-mentioned devices.

It is important to realize, that this kind of technology has not been developed in one step but are the result of a long incremental chain of developments. The Iphone, which revolutionized communication as much as computer technology in general, was the result and combination of many ideas which were realized beforehand as separate devices: The cell-phone, pocket-computer and organizers, digital cameras, music players and many more. Usually the innovative technologies take a long time to catch on, in which only ‘early adaptors’ go through the trouble of using devices not yet fully developed. More than other aspects of functionality ease of use is missing during these early stages of development, because broad testing, trouble shooting and rounds of re-designing until the wider public being willing to use the new technology.

As much as the technological improvement the success of ‘Building Monitor’ will depend on a more or less conscious cost-benefit-analysis by the potential customers. An important achievement of the pathfinder was the identification of a focus group for which the first modells of building monitor can be marketed: The home owners which already have invested in their houses and have a natural interest in improving the building performance. A landlord might neither be interested in reducing energy costs for his or her tenants nor to raise awareness to potential deficits in the indoor comforts. The homeowner profits from the energy savings as much as from the improvement of his or her well-being.

Still the price range of the product according to the perceived benefits is essential for the marketability. Here the potential for a low price product is large. If ‘Building Monitor’ manages to make the functionality of monitoring systems, which nowadays are only available in large commercial buildings or scientific research projects available for everyone within a price range which relates to the perceived benefits, the market potential is enormous. Here the outlook for building monitor is good. The technology on which ‘Building Monitor’ is built upon will not only become cheaper but also more often become part of the standard building equipment. This is particularly true for smart meters and building components, which are designed to be controlled and communicate via internet and / or WIFI like heat pumps. This will lower the costs for the initially investment for the hardware components of ‘Building Monitor’. At the same time it will widen the range of possibilities, what ‘Building Monitor’ can do.

Displaying information and communicating with the inhabitants is only a first, but important stage of ‘Building Monitor’. It is clear, that in the near future not only building equipment (smart meters, heat pumps, air condition, lighting, multi-media etc.), but also appliances (washer, dryer, washing machine, refrigerators etc.) and building components (doors and windows etc.) will become increasingly automatized and interconnected. This connectivity is a very big opportunity for the improvement of the building performance and level of comforts for the inhabitants at the same time. But it can only be effective if a comprehensive system connects and controls the components. This is not a mere technical challenge. More than anything the success and failure of the super-connected and highly automatized home of the future will depend on the question, how good the communication between the building, its users and modelling (‘understanding’) of the needs and wants of the inhabitants is. Here ‘Building Monitor’ offers a new approach which does not start from a technical challenge, but from the wants and needs of the human being.

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