MSc Program
Renewable Energy in Central and Eastern Europe

Technological Potential of an Advanced Concept for Heating System Control in Buildings

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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22.11.2013, Vienna

Affidavit

I, György Barta, hereby declare

1. that I am the sole author of the present Master's Thesis, "Technological Potential of an Advanced Concept for Heating System Control in Buildings ", 70 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Abstract

The COTIMO concept represents an Energy Efficiency technology which saves heating energy of buildings. It does its job through a unique intelligent control of the heating system.

This technology can save easily 5 to 10% heating energy per year. The cost of implementation is cheap compared to other energy efficiency alternatives. The operation of the concept is described in this work. Measurements, simulations were done to get almost real saving data. These efforts let an insight to the performance of the concept.

In 2013 the world’s population consumes more than the earth can give. Sustainability questions arise again and again regarding energy, air, water. After years long study of different renewable energy solutions, one thing has to be told: using Renewable Energy always has to be the second step. Energy Efficiency comes first.

The concept works best at buildings with low RC time constants and at low frequency occupancy changes. The simulations resulted saving values between 2% and 11%. This domain is lower than other papers declare in the literature. It is not recommended to install the system in case of high frequency occupancy changes. In such cases the building’s heat consumption may be higher than without the system.

Cinemas, conference centres, weekend houses, university auditoriums, schools, sport halls, churches are only a few examples where the concept may be successful.

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Acronyms

EE	Energy Efficiency
RE	Renewable Energy
WSN	Wireless Sensor Network
DHW	Domestic Hot Water
CPS	Cyber-Physical System
HVAC	Heating, Ventilation and Air Conditioning
PCB	Printed Circuit Board
LTI	Linear Time-Invariant
IT	Information Technology
R_{th}	Thermal Resistance [K/kW]
C_{th}	Thermal Capacity [kWh/K]

Summary

The COTIMO concept represents an energy efficiency technology which saves heating energy of buildings. It does its job through a unique intelligent control of the heating system.

In the COTIMO concept occupancy sensors or motion detectors detect the occupancy of a room or zone. A server processes the gained data and tries to set up trends. The control system regulates the temperature in a room according to its predicted occupancy.

The concept gets analysed through simulations. The simulations are based on field measurement of buildings with existing automation systems. Out of the system's database energy data was possible to gain with data mining techniques. This measurement data allowed the determination of the thermal properties of the buildings. Simulations were done using the pre-calculated thermal properties.

Matlab Simulink simulations were performed with real 2012 climate data to calculate the whole year consumption of the buildings. Both heating with and without COTIMO were simulated. And after simulations comparisons were made in order to detect the benefits and handicaps of the concept. The work contains 3 field measurements and 12 simulations. An extra 3 dimensional representation is provided to unveil the coherence between the potential saving and the building's thermal properties. This 3 dimensional plot is the result of 200 extra simulations.

The simulations showed that a rarely visited building (for instance weekend house) can reach 10% saving in heating energy per year. In a larger building 10% of the heating costs is a big amount of money. The concept works the best in huge rarely used poorly insulated spaces. In this case the saving by the concept can reach up to 50%. In other more realistic cases the saving is easily between 5 and 15%.

The investment cost of the implementation of an advanced energy monitoring and control system varies. Customised solutions are well fitted to the needs, but require experts and many working hours to develop and test the system. Customised solutions are more expensive.

Commercial solutions are easy to implement, and they are also robust, but a high level synthesis of the different type of devices is rarely achievable. These systems are cheaper.

Cinemas, conference centres, weekend houses, university auditoriums, schools, sport halls, churches, any kind of bad insulated, bad geometry buildings are motivating targets. Bad insulated old buildings are interesting.

Very good niche market can be the category of historic buildings, where no facade renovation is permitted. Owners of such buildings would possibly invest in such an EE measure.

1 Introduction

In 2013 the world’s population consumes more than the earth can give. Sustainability questions arise again and again regarding energy, air, water. After years long study of different renewable energy solutions, one thing has to be told: using Renewable Energy (RE) always has to be the second step. Energy Efficiency comes first.

1.1 Motivation

Why do somebody today cover the roof of his house with photovoltaic panels? Probably he wants to cut some electricity costs. Did he really do what is the best for him? In case he has still wolfram lightning bulbs: no! In case he had already replaced all the lightning bulbs to led bulbs: yes! He did an economic right decision only in the case, he first worked for maximum energy efficiency in his house.

Moving onto the macro scale the humanity faces sustainability questions. Will our children breathe the same fresh air as we do? Will our children drink the same quality water as we do?

Many people say that too many of us live on the earth, and there is no room enough for so many. Others share the opinion that there should be more consciousness and brightness regarding sustainability questions, so mankind can create a sustainable world. The fact is that there is more than enough energy out there; the only challenge is to put it into our use.

Humanity is in time. Too many changes cannot be expected in a short time. This would lead to anarchy in some cases. Oil and natural gas are some sort of gifts from God to let humanity able to start its journey towards scientific enlightenment. The demand on fossil fuels worldwide nowadays reaches its top, but it is all right. Now mankind needs to use God’s gift in order to develop more effective and sustainable techniques to keep the earth clean and versatile on a long term.

In such an environment engineers can find enough challenges, they should feel responsible towards coming generations. Businessmen should make money in such a way that the earth gains also with it.

Considering financial aspects, Energy Efficiency (EE) projects may be profitable even without subsidy. Return period as long as 5 years is common for Energy Efficiency (EE) projects. In terms of Renewable Energy (RE) return periods are usually 10 years or more. Subsidy schemes distort the market and support an unhealthy development.

Technologically seen the biggest driver of the EE industry is the development of smart and “communicative” devices. Devices and technology for the measurement and logging data in energy systems are widely available.

Today almost everybody has a device appropriate to control an intelligent home. This device is called mobile phone. Mobile phone producers provide phones with bigger and bigger performance for cheaper and cheaper prices.

A brand new direction of research is the research of Cyber-Physical Systems (CPS) This trend aims physical systems to undergo computational control. An energy system is a physical system, which we really want to let undergo our control to reach high efficiencies.

The CPS opens very interesting directions of development in many fields of our lives, but also makes us humans vulnerable. A CPS is usually so complex that they require automatic control. This mix is dangerous. Somewhere a “robot” decides whether our boiler works or not, or the ventilation in our house runs or not.

Smart homes are more and more popular. Most of the people think this is something expensive and gives only comfort. This is in some cases only a part of the truth. Smart or Intelligent Houses can be very energy aware. A house which gathers outside and inside temperature data, gathers PV data, and in case inside temperature is low and outside temperature is high, starts airing to heat the house. Or in case both inner temperature and outside temperature are low, but the PV panels produce a lot of electricity (so there is solar radiation out there), the shutters go up to let the sunshine in.

This means that Smart Homes can give much more than comfort. They can give energy efficiency as well.

1.2 The core objective of this work

The goal of this work in some manner is to contribute to an energy efficient world with some sort of knowledge and experience. In some manner there are also business opportunities in this field. This mix makes the topic quite interesting.

The most important goal of this work more precisely is to analyse the energy saving potential of the COTIMO-concept, under which circumstances it is worth to implement under which it is not.

A less important goal is to develop a model with which some special Energy Efficiency measures can be simulated. This model can have further use; it can be the basis of a future application which is useful to estimate savings. A useful tool for the engineers and technicians to decide if it had sense to implement the system, or to decide what type of system had to be installed.

Europe has a long history with many beautiful patina buildings. Historic buildings are our heritage, so we have to maintain them for coming generations. There is a lack of efficiency technologies on historic buildings. The reason is, that no facade insulation is allowed. This work aims to find a solution which offers an opportunity to historic buildings be more economic.

Buildings built in the 60’s, 70’s have bad thermal properties and often owned by not wealthy residents. The reason why these buildings have bad thermal properties is that in that time the price of energy was very cheap compared to today’s energy prices. As mentioned this people are not wealthy, and sometimes they cannot finance the refurbishment of such a building, but now this work can provide an alternative technic to help them.

In a bad insulated house the day-night temperature control can reduce a heating energy demand by 20 % or more. In Eastern Europe bad insulated houses dominate. This study focuses on savings earned only on heating.

1.3 Structure of Work

In order to see the roots of the result of an experiment, sometimes new theories have to be introduced.

The topic the work focuses on is energy efficiency in buildings. Answers are given to the questions like why this topic is chosen and what are the properties of this field.

The work approaches energy efficiency through intelligent energetic monitoring and control of buildings. Energy monitoring and control possibilities are described later.

Basic theories are presented like electro-thermal analogy and thermodynamics basics.

Field measurements were performed to precisely determine the properties of the buildings.

The simulations are based on field measurement of buildings with existing automation systems. Out of the system's database energy data was possible to gain with data mining techniques. This measurement data allowed the determination of the thermal properties of the buildings. Simulations were done using the pre-calculated thermal properties.

Matlab Simulink simulations were performed with real 2012 temperature data to calculate the whole year consumption of the buildings. Both heating with and without COTIMO were simulated. And after simulations comparisons were made in order to detect the benefits of the concept. So the work contains all together 3 field measurements and 6 simulations.

Lessons learned with the help of simulations are introduced and analysed. The COTIMO behaviour of the buildings are compared, and conclusions are made.

There are some rules of thumb set up which are easy to use in case a specialist wants to estimate a building's saving potential without running a complex simulation. A useful tool for the engineers and technicians to decide if it had sense to implement the system, or to decide what type of system had to be installed.

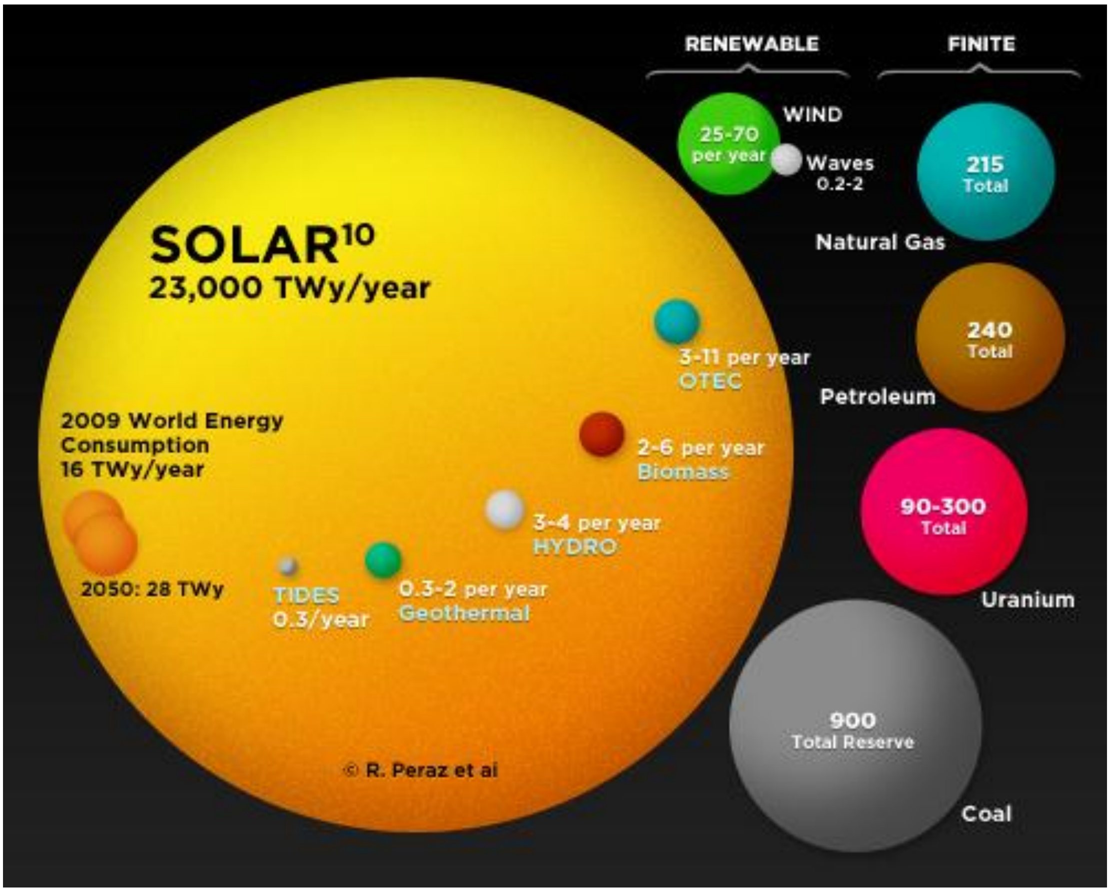
Emphasis was placed on the visualization of the results. A 3 dimensional surface plot demonstrates the correlation of the thermal properties and the energy saving potential of a building. To develop this plot 200 simulations were performed.

2 Background Information

The topics in this chapter contain information which help the reader to understand further chapters. The reader finds information why “energy efficiency comes first”, what are Smart Homes, what is energy monitoring etc. Energy Management today is definitely a growing industry, so this work wants to give the reader an insight.

2.1 Energy Efficiency

To locate the real issue regarding energy we first need to deeply understand the message of Figure 1. It shows, that in 2009 the world’s energy consumption was 16 TWy (Terra Watt year). Terra Watt year means 8760 times TWh (Terra Watt hours). The predicted consumption for 2050 is 28 TWy. The earth’s total petroleum reserve is 240 TWy. Total uranium reserve is 90 to 300 TWy. This means 900 TWy coal in total.



1. Figure - Total Energy on Earth (Perez 2009)

Among renewables wind has the second highest potential behind solar energy. Wind has a global potential of 25 to 70 TWh/year.

Solar irradiation is 23 000 TWy/y, not in total but per year. This is huge. Solar irradiation per year is hundred times more than the total petroleum reserve on earth. Or solar radiation in a year is ten times more than the earth's other fossil energy carriers plus uranium together.

The above mentioned facts mean that humanity faces no energy problems, but energy efficiency problems. Humanity has no technology yet to efficiently use the given enormous volume of energies.

This work turns many times back to the fact that energy technology improvement is the key to reach energy welfare on earth.

2.2 Smart Homes

Most of the people have already heard about Smart Houses or Smart Homes. Most of them think this is something which is expensive and gives only comfort. This is sometimes only a part of the truth. Smart or Intelligent Houses can be very energy aware. A smart house may collect outside and inside temperature data, may gather PV data, and in case inside temperature is low and outside temperature is high, the house may start airing, to heat the house. Or in case both inner temperature and outside temperature are low, but the PV panels produce a lot of electricity (so there is solar radiation out there), the shutters go up to let the sunshine in.

This means that Smart Homes can give more than comfort. They can give energy efficiency as well. Let's see another example of energy aware Smart Homes. Imagine a building having ventilation system. The ventilation system consumes electricity and the building suffers heat loss during the ventilation. The building loses not that much that it would in case no ventilation system was installed, but still something. What to do to minimize the ventilation? Answer is CO_2. The server of a Smart Home can receive data from CO_2 sensors and can give command to the ventilation system to heat or not. Or the server can send a pre-calculated m^3/h value to the ventilation system to keep.

This means Smart Homes need to be distinguished. There is a non energy-aware and there is an energy-aware type of Smart Homes.

“Internet of Things” is a hot topic today. It means that each electronic device in a household is capable to communicate with another electronic device. A brand new platform for this type of networking is Digital Living Network Alliance DLNA (DLNA Connect and Enjoy 2013). Manufacturers of electronic devices can produce DLNA ready equipment, so this equipment in a household will be a node in a very sophisticated information network. DLNA now seems to be more for comfort and less for energy efficiency, but it is a good initiative.

2.3 Energy Monitoring and Control Systems

There are many variants of data acquisition and control systems. It is better to say, that there are many variants of implementations, the principles are always the same.

2.3.1 Systems

There are many forms of energy used in buildings. These are electricity, Domestic Hot Water (DHW) and the energy for heating. DHW and heating energy are not always easy to measure. In the case both are generated by separate electric boilers the situation is very lucky, but this scenario has a very little chance. In a more realistic case one natural gas boiler heats both the DHW and the heating system (radiators). In this case the heat carried through the pipes has to be measured. Therefore machinery intervention and expensive thermal mass flow meters are needed. There is a research direction which makes the flow measurement easier to implement: (Simone Dalola 2012).

Some companies are specialized and monitor only electricity. They use a network of electricity meters to detect and localize the extraordinarily big consumptions. Old electrical devices can consume a lot for two reasons. One is that in the old times energy efficiency was not a question. The other is more technical: the insulations made of plastic aging and this causes leakage of electricity even in standby mode. With a temporary installation of electricity monitoring system the weak points can be determined and repaired or replaced. Further information regarding specialized electricity metering systems: (The Energy Detective 2013).

Some companies offer complex solutions for the industry. Industrial appliances have to fulfil high standards therefore they cost more. Availability is crucial point. Meanwhile a latency of a monitoring device at the production line is unacceptable; a couple of minutes delay of the energy data for energy management is absolutely all right. More about industrial energy metering: (Johnson Controls 2013).

Some companies are more interested in residential solutions: (Smart Home 2013).

For this work a very cost-effective system was chosen: (HomeMatic 2013). This company provides a broad range of monitoring devices: inside-, outside temperature, humidity, CO_2 for air quality, occupancy and even wind speed. Hundreds of such sensors can be attached to a central device which is connected to a server to gather the data. These devices are not really accurate, but cheap and easy to install, so it is affordable to really use plenty of them.

Both data acquisition and control can be *wired* or *wireless*. Wireless solutions exist in the recent years only. They consume low energy for their communication. This means: this kind of data-gathering devices can operate with a couple of AA batteries almost two years long.

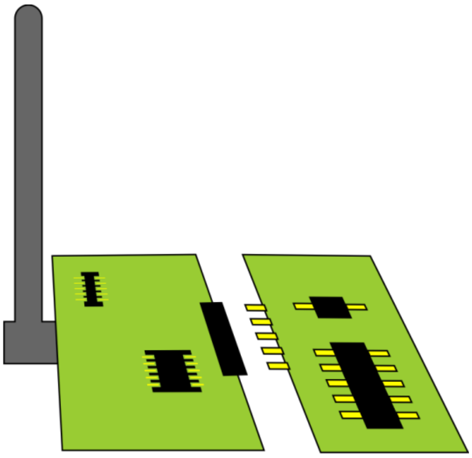
These standards called the topic “Internet of Things” alive. Such communication standard is the IEEE 802.15.4 Standard.

It is important to mention the expression *Wireless Sensor Network* (WSN). WSN is a cyber-physical system (CPS), where a sensor and a communication module together form a simple, low consuming device. Many of these devices build a WSN. There are many types of topologies a WSN can work. Further information regarding Wireless Sensor Networks: (Sultan 2010).

2.3.2 Hardware

Figure 2 demonstrates a typical uncovered WSN end-device hardware setup. On the left hand side there is a universal communication unit with external antenna to reach long distances. Some of them have the antenna mounted on the board. These communication units have very low consumption thanks to the communication protocol. They “sleep” all the time -means that they are shut down-, they wake up once in a minute and transmit the measured value in a very short time range like 100 milliseconds.

They run years long without the need for changing the battery.



2. Figure Demonstration of a PCB based Communication Unit with its attachable Sensor (György Barta, 2013)

On Figure 2 on the right side there is a sensor can be any kind. The two elements have a port in between where only a value has to be transmitted from the sensor to the communicating device.

The attachable sensor can measure temperature, humidity, CO_2 or even SO_2 and O_3.

2.3.3 Energy Services

The technological overview above shows that today it is possible to give “nervous system” to a building. Data is never enough to achieve energy saving. For energy saving the data has to be processed, so a ”brain” is also needed. Servers and appropriate software do the processing. The computational time is a function of so called *nodes* (number of sensors) and the *logic* needed for the building. This means that a small building with a few sensors and easy logic requires a simple personal computer. Big office buildings with many sensors and complex logic can use out many enterprise-class servers.

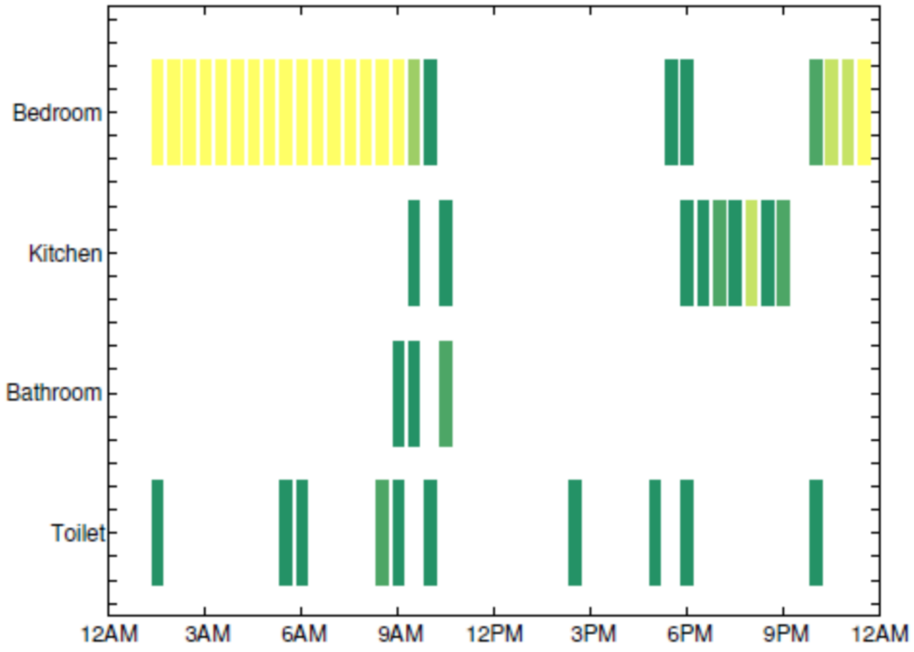
Processed data gives infinite possibilities in terms of energy consciousness. As Haas (2010) introduced the theory of Energy Services it is obvious, that Energy Services are not only dependent on the quantity of the energy, but also on the efficiency of its usage (Equation 1).

S is the Energy Service, E is the energy used, η is efficiency, T is technology.

$$S = E \cdot \eta(T)$$

1. (Equation for Energy Services (Haas 2010))

According to Haas (2010) humans do not need energy for buildings, they need good temperature in the building. People don't want to use patrol, they only want to have transportation. So people need Energy Services, not energy.



3. Figure - Occupancy of Rooms in an average household (Tamim Sookoor 2013)

According to Haas (2010) energy efficiency, energy technology needs development on the first place. This idea necessarily involves smart technology. Pilot projects show that even positive energy balance houses can be created: (Klemport 2013).

Positive energy balance is when the building generates more energy than it consumes. Such systems necessarily use energy monitoring systems. This is how they prove the positive balance.

In a building people need good temperature only where they are. This means knowing when and where the people are in a building gives a good opportunity for energy saving. Tamim Sookoor (2013) placed motion detectors in a couple of rooms in an apartment. He got the following result (Figure 3).

The areas on the picture show motions in the room, their colour represents the intensity of the motion.

As Figure 3 represents there is a low occupancy in a room in general. For example the toilet’s usage is well distributed in a day, but for example the bathroom is rarely used but longer. The heating of rarely but longer used rooms like bathrooms should be ON only before it is used. It is useless to heat a room without being used.

In rooms like the toilet the trick doesn’t work. It is hard to predict the time of the usage, and in case it is predicted there is only a little energy to be saved.

Saving is achievable when a room’s usage is periodic. Periodicity means predictability. So in case a room’s occupancy is more or less periodic it’s usage is predictable. For energy saving this property is very important, because heating systems are sluggish; they have a big inertia, so it takes a long time to cool down a room, and also to heat it up.

Energy Monitoring can have an effect on the person’s thermal comfort in the building. Measuring the temperature in each room means knowing the temperatures in each room. With this knowledge heating systems can be fine adjusted, fine-tuned. This is beneficial for both thermal comfort and energy efficiency reasons. According to Richard Sickinger (2012) the thermal comfort is an exact measure and can be calculated.

In more complex energy monitoring systems, alert subsystems can be implemented. This continuously observes some crucial values and gives alert in case the value goes out of the normal range. Alert subsystems can send even short messages via cellular network (GSM) to the service personal.

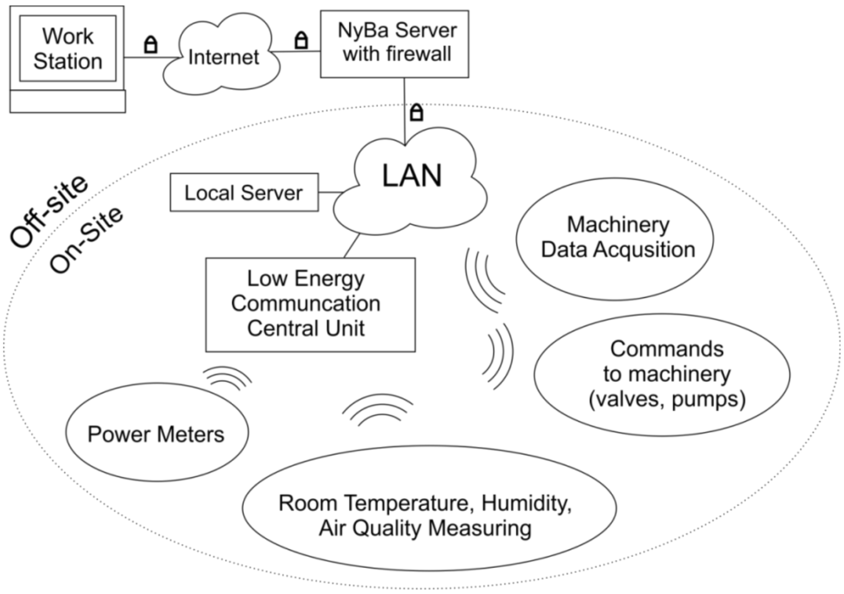
2.4 Data Acquisition and Remote Monitoring

A schematic representation of the data acquisition and control system can be seen on Figure 4. It is obvious that the center of wireless devices is the called “Low Energy Communication Central Unit”. This is a gateway.

Gateway is a device which brings together two communication systems of different protocol. On Figure 4 the above mentioned gateway is the link bet.ween the Local Area Network (LAN) and the Wireless Sensor Network (WSN)

The Local Area Network (LAN) communication network is the basement of the implemented system. It is evident, because it is cheap to build up and it is provided in almost every buildings due to this is the network of the widely spread internet.

Gateways are connected to the LAN. Specialists use different kind of systems mixed together so they use a hybrid. This is due to the fact that systems have very different properties. For a WSN in all cases it is very important that the devices consume little. Wi-Fi systems are not able to run on battery for years, but ZigBee devices do. However Wi-Fi has very high speed compared to ZigBee.



4. Figure - General Schematic of an Energy Monitoring and Control System (György Barta, 2012)

To implement remote monitoring the server has to be accessible through the internet. Therefore a fix IP address is needed. There are two possible philosophies regarding servers. One is that server is on the site, another is that server is off-site. Both have advantages and disadvantages. If the server was on-site the system is fast, and in case of internet outage the system works smoothly further. Disadvantage is that it is more complex to update the server. If the server was off-site update is easy, but in case of internet outage the monitoring system cannot work.

Building up hybrid systems is also possible. In this case there is an operational (slave) server on-site, and there is a logging and processing (master) server off-site.

The slave server makes sure that in case of no internet connection the system works further properly. Slave servers do not need systemic level update; they get always updated by the master server when internet connection is available.

The server logs data, runs processes, makes visualisation, builds up the user interface automatically and functions as a web server. It is accessible via internet browsers and via client applications. Secured communication (for example SSL) is suggested to protect important data and to avoid attack.

Cyber-attacks are more and more regular. This means a remote-controllable building is more than vulnerable. Imagine your boiler heating crazy whole day and when you arrive home you notice that there is 35 °C inside, all your foods went wrong and your pet is not having a good time. Not talking about the money wasted.

Hackers have robust techniques to hide. This means it is either better to avoid remote-control or make it very secure. Remote Monitoring is another topic, it is not interesting for hackers.

2.4.1 Electricity Metering

The technological development of communication devices made electricity metering easy. Power meters with communication facility are available in many forms: bus-mounted, socket mounted etc. Often the same gateway connects them to the LAN network.

5. Figure - Socket Based Power Meter

Power monitoring gives us the possibility to locate malfunctioning, or inefficient devices. It gives information enough to plan an investment on cost reduction.

Figure 5 shows a socket power meter. This is only one type; there are many other types like clamp meters, electricity meters for DIN rails. DIN rail meters are the most spread types.

The fact has to be mentioned, that these types of devices separately don’t tell too much about the building. It is a hard work to walk through the building and read these devices. And this is what the reader did once, and knows the actual power consumption, and the total energy consumption. This is still nothing compared to a system, where a minute based power counter works, and the data gets automatically gathered. The user sits in front of the user interface and sees beautiful graphs of data representing the power consumption of different devices or circuits.

Appropriate representation of this huge volume of data is essential to let a specialist be able to draw conclusions and to make saving decisions. For example in the case the power consumption of same type of electrical devices are observed, a comparison chart is very useful to determine a malfunctioning device.

2.4.2 Heat Metering

Unfortunately in some cases specialists face the challenge they have to measure the heat carried through pipes in order to calculate costs. This phenomenon is solved for a long in industrial systems, but not in buildings, especially not in small buildings. Thermal mass flow meters are expensive, and there are many aspects an engineer has to consider at the planning of thermal mass flow metering.

As mentioned in the case heat carried through pipes has to be measured; machinery intervention and expensive thermal mass flow meters are needed. According to Simon Dalola (2012) new PCB based sensors may revolutionize the segment.

2.4.3 Temperature Metering

Everybody knows what a thermometer is. Thermometers measure temperature. There are thermometers for measuring body temperature, for measuring inside room temperature, and there are thermometers to measure outside temperature. The very widely used thermometers are capable to show only the actual temperatures. They cannot store previous temperature values. Reading them occurs visually with the eyes.

Let’s suppose that somebody wants to record the temperature in his bedroom and the outside temperature with a usual type of thermometer. He has a hard work. He needs to read the temp. values and log them in a notebook. Precisely each day in the same time. This is where people starts to be grateful to the technical development of mankind. Wireless Sensor Networks (WSN) are designed to take over this activity.

In the WSN temperature meters are real end-devices. They only measure. They send the temperature data in each minute. Hundreds of such meters can be implemented in a system, and the temperature data get collected very organised in a database.

Most of the temperature meters also measure humidity. There are indoor and outdoor temperature meters for different temperature range. Outdoor meters are waterproof.

2.4.4 Multi-Temperature Metering or Room Zoning

It is very interesting that boilers are installed by mechanics. Most of the mechanics don’t have a clue about systems control. People cannot estimate the importance of a fine-tuned heating system so they sometimes underestimate its significance. They very rarely let a team fine-tuning a system.

Boilers have a thermostat input. Without a thermostat signal the boiler is unable to work. So mechanics buy a thermostat and fit it to the boiler. Now the question arises: where to place the thermostat? If it is placed to the coldest part of the house it is pretty sure that nobody and nothing will freeze, this is attracting. Most of the cases mechanics place it to the coldest part of the building thinking “sure is pretty sure”.

Is this good? Well with one thermostat probably the most responsible choice. But in many rooms the temperature can be so hot that the window has to be opened. This is a useless waste of energy and money.

As mentioned before mechanics rarely fine-tune the heating systems. This Is due to the fact that heat up-, or cool down times are long in a building. This leads to a heterogenic temperature distribution in a house. This means one room gets warm, another room gets cold. This indirectly leads to waste of energy.

Let’s talk about the case when the thermostat is placed next to an airing window, or an often open door. The boiler will run in each and every case the window or door is open. The thermostat in this case does not represent the average temperature in the house.

There are two solutions to solve this phenomenon. One is called multi-temperature metering. The other is called room zoning.

At multi-temperature metering many thermostats are placed in the building. They send their temperature data to a central unit. Average is calculated and this average temperature goes to the boiler as actual inside temperature. Advantage is that opening a window will not start the boiler.

A more sophisticated solution is the room level zoning. The difference between multi-temperature metering and room zoning is that for room zoning the room’s temperature can be freely set, at multi-temperature metering not. So measurement is ok in both cases, but at multi-temperature metering there is no opportunity to separately set room temperature.

2.4.5 Occupancy Sensing

Today there are two main fields where occupancy detection is used. The fiels are lightning control and asset protection. There are two major arts of sensing occupancy: motion detectors and occupancy sensors are both acceptable.

With the help of the occupancy data gathered by a network of motion detectors or occupancy sensors a routine can be calculated in each observed rooms. This is exactly what Tamim Sookoor (2013) did and produced Figure 2.

2.4.6 Heat Control

Heat control in a building is in most of the cases static. The valves and pumps are set properly at the beginning of operation. At room level zoning the temperature of the rooms need to be set separately and dynamically. There are adjustable valves available on the market, with which zoning is possible. Most of the adjustable valves need to be installed by mechanics, but there are ones which can be easily mounted on the radiator instead of the old manual valve. Figure 6 on the left hand side shows such a valve adjuster.

On Figure 6 next to the valve adjuster there is a thermostat which one works very sophisticated. Both devices are wireless. The thermostat first of all needs to be paired to the valve adjusters with whom he is in the same zone. Maximum four valve adjusters can be paired to one thermostat. The thermostat can send the control signal to the valve adjusters directly. This is only one function of the thermostat. The other function is to link the zone to the complex energy monitoring and control system. Only the thermostat keeps contact with the central unit the valve adjusters only with the thermostat.

The thermostat can decide the valve settings autonomously. As mentioned the thermostat sends out the control signals to the valve adjusters. The central unit defines the target temperature, but the thermostat can decide how to reach it.

6. Figure - Wireless Thermostat and Radiator Valve Adjuster (György Barta, 2012)

Figure 6 represents very special devices. And yes this system works only at radiator based heating systems. Actuators are the devices whom can send out control signals everywhere they are placed. So this is why almost everything is controllable in an energy monitoring and control system. Other elements of the machinery like ventilators, pumps, valves can be easily controlled by actuators.

2.4.7 Remote Control

It is possible to run the energy monitoring and control system in offline or island mode. It has a big advantage, namely it is safe. It is almost impossible to reach the server outside of the LAN. Security experts say, that mankind can never reach 100 % security.

Figure 7 shows a picture of the screen of an electronic device running the monitoring and control application of a house. Touch screen devices give priceless possibilities to make such systems attractive to end-consumers. The user interface gives easy access and control of the building. Even technique aversive people can understand the meaning of the different numbers and buttons.

7. Figure - User Interface of an Energy Monitoring and Control System (György Barta, 2012)

Imagine the remote control for the television. This device is also a remote control but not for a television but for a home. It is a freely programmable and customizable interface which keeps contact between the user and the server.

The frame of the interface is provided; the developer only needs to put the puzzle together. The interface runs on each tablet- and mobile phone platforms.

At remote access the authentication is crucial. On the login page at least a strong password is essential to protect the server against hackers. But once security is solved the building is controllable from anywhere. This is an attracting property

3 Methodology

The goal of this work in some manner is to contribute to an energy efficient world with some sort of knowledge and experience. In some manner there are also business opportunities in this field. This mix makes the topic quite interesting. More precisely the goal of this work is to analyse the energy saving potential of the COTIMO-concept. Under which circumstances it is worth to implement under which it is not.

In the COTIMO concept occupancy sensors or motion detectors figure out the occupancy of a room or zone. A server processes the gained data and tries to set up trends. The control system regulates the temperature in a room according to its predicted occupancy.

For those, who are not familiar with some basics like electro-thermal analogy or thermodynamics a short introduction is presented.

The concept gets analysed through simulations. The simulations are based on field measurement of buildings with existing automation systems. Out of the system’s database energy data was possible to gain with data mining techniques. This measurement data allowed the determination of the thermal properties of the buildings. Simulations were done using the pre-calculated thermal properties.

As one of the core objectives of this work is to develop a model where different energy efficiency measures can be simulated; the model is built and introduced, and used further to give basis for further investigations.

Matlab Simulink simulations were performed with real 2012 temperature data to calculate the whole year consumption of the buildings. Both heating with and without COTIMO were simulated. And after simulations comparisons were made in order to detect the benefits of the concept. So the work contains all together 3 field measurements and 6 simulations.

Lessons learned with the help of simulations are introduced and analysed. The COTIMO behaviour of the buildings are compared, and conclusions are made.

There are some rules of thumb set up which are easy to use in case a specialist wants to estimate a building’s saving potential without running a complex simulation.

A useful tool for the engineers and technicians to decide if it had sense to implement the system, or to decide what type of system had to be installed.

Emphasis was placed on the visualization of the results. A 3 dimensional surface plot demonstrates the correlation of the thermal properties and the energy saving potential of a building. To develop this plot 200 simulations were performed.

The author puts some effort into the determination of some possible target markets for the concept defined in this work.

4 The COTIMO-concept

In this chapter the COTIMO concept is introduced. This work aims to analyse the opportunities this concept can give.

4.1 Detailed Description of the Concept

The name COTIMO is composed of three words: cost, time and money. The core idea is that the average occupancy of a room is very low (see Figure 3). Why do schools heat the classrooms on the weekends? Why do office buildings have the same temperature at night as they have during the day? Giving answer to these questions is not easy, because it is sometimes more efficient to heat the office buildings also at night rather than turning down the heating.

In the COTIMO concept occupancy sensors or motion detectors detect occupancy in a room or zone. A server processes the gained data and tries to set up trends. The control system regulates the temperature in a room according to its predicted occupancy. This means occupancy sensors, thermostats and controllable radiator valves are installed in the involved rooms or zones.

If the system reacted at the time of occupancy that would be a way too slow. The concept has to be able to predict occupancy with any degree of accuracy. The “predicting part” of the concept is considered as a black box, but the reaction of the system is discussed here.

4.1.1 Important Variables

For a proper answer on the change of circumstances many variables have to be defined. A complete set of variables are defined to understand the dynamics of the control system and the dynamics of the building.

Presence

The presence is the presence in a room measured by an occupancy sensor, or motion detector. This variable can represent only the present and the past.

Possibility of Presence

Possibility of presence is also a time-dependent variable which represents the future. It is generated by the black box.

Real Outside Temperature

The real outside temperature is the measured outside temperature. This variable represents the present and the past.

Outside Forecast Temperature

The outside forecast temperature is a prediction of the outside temperature. This is essential to plan when to start heating a room. Today weather forecasts are online available. These weather forecasts are pretty accurate considering the coming two-three days. This interval is more than enough from our aspect.

4.1.2 Regulation

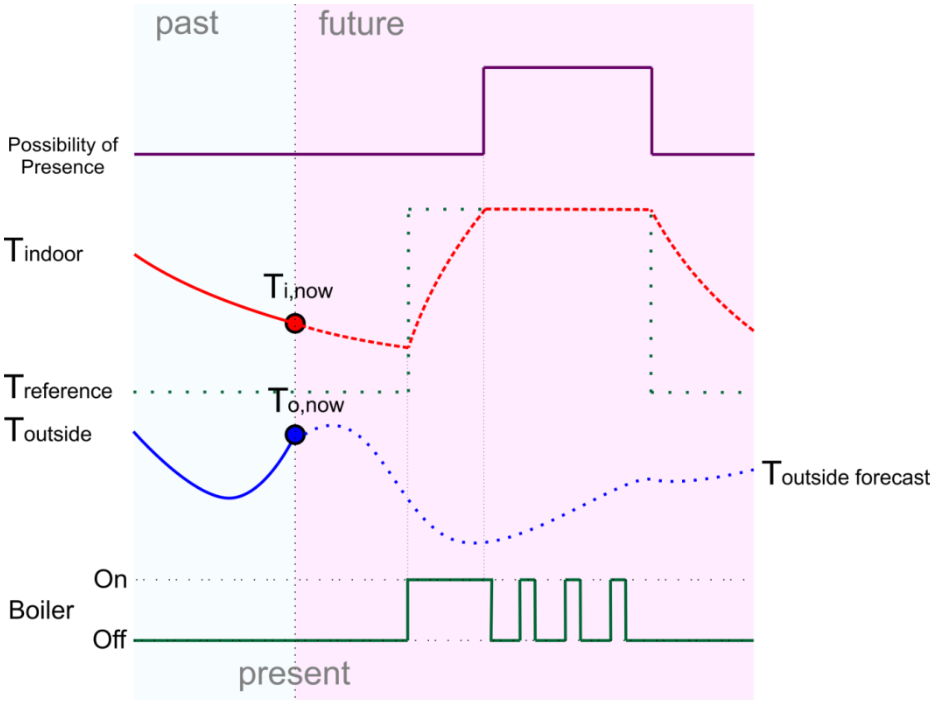
The possibility of presence is always provided by the black box. The reference temperature $T_{reference}$ (Figure 8) is a function of the indoor temperature, outside temperature, possibility of presence, the building's thermal properties and the performance of the boiler. Once the reference temperature rises -due to an increased possibility of presence-, the boiler heats till the indoor temperature reaches $T_{reference}$.

As possibility of presence decreases, the reference temperature goes down again and so the boiler won't heat. The indoor temperature decreases until it reaches the low reference temperature. This is the anti-freezing mode or standby mode.

Once the possibility of presence rises again the reference temperature dictates a start to the heating system well in advance. The calculation of the reference temperature is not part of this work.

On Figure 8 the green half-plane represents the past and the red half-plane represents the future. Measured temperatures are on the green half-plane, and forecasts are on the red half-plane.

For the calculation of the reference temperature system data is needed in order to know when to start heating the building to reach the wanted inside temperature untill the time of presence.



8. Figure - Schematic Representation of the COTIMO Control (György Barta, 2013)

To put it in easy words. The possibility of presence follows the occupancy of a room or a zone. The reference temperature follows the possibility of presence, and the indoor temperature follows the reference temperature. Such a complex system is needed to go through the challenge.

4.2 Theoretical Energy Efficiency Potential of the Concept

Let's observe the real occupancy in one of the rooms at a workplace. A usual number of working hours a day in Europe is 8 hours. This is 1/3 of a day. There are weekends with which the altogether occupancy is 1/3 times 5/7. This is 23,8 % and national holidays are not calculated.

From energy saving perspective the picture looks different. A percentage doesn't tell anything. Let's imagine each fourth second minute there is an occupancy; the room has to be heated all the time. The altogether occupancy is 25 %, but there is no possibility to introduce the involved energy efficiency measure.

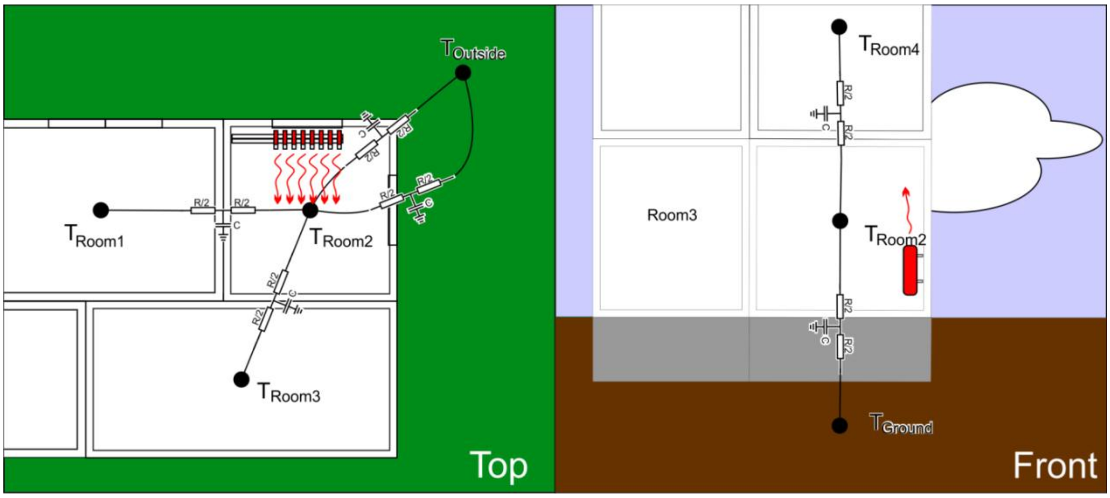
More important are the “non-occupancy holes” in a building’s occupancy diagram. Thermal resistance and thermal capacity play also a big role. Theoretically 50% saving or even more is achievable.

5 Heat Dynamics of Buildings

Each building has thermal properties. The thermal properties depend on two major factors: the thermal resistance R_{th}, and the thermal capacity C_{th}. Primarily windows, wall insulation, and geometry of the house define the thermal resistance of the building. Mass of the building defines the thermal capacity. Most of the buildings are designed to keep the indoor temperature constant, or at least in a domain.

Solar irradiation can also play a significant role in the building’s thermal behaviour especially at sunny locations and/or big window surfaces.

To be able to dynamically simulate the buildings response to the outside circumstances a unique approach was chosen (See chapter 5.1).



9. Figure - Representation of the Resistance and Capacity Elements of a Thermodynamical System (György Barta, 2013)

Figure 9 shows two perspectives of a room in a building. The temperatures are indicated by thick points. The thermal fluxes are indicated by lines. Two effects meet the thermal flux. One effect is an “obstructing effect” (resistance) and the other is a “delaying effect” (capacitance).

Where is a temperature gradient there is a heat transfer (see Equation 2). On Figure 9, Room 2 has constant temperature. Each neighbouring medium of the room has different temperatures. The temperature difference between the room and its surrounding and the thermal properties of the intermediate medium (walls) together define the heat transfer.

Room 2 has a heat transfer to Room 3, to Room 1, to the outside (through the walls and through the windows), to the ground and to Room 4. Heat transfer can be negative, when Room 2 has higher temperature than its observed surrounding, or can be positive, when the surrounding has higher temperature.

5.1 Theory

The usual u-value based calculation of a building's thermal behaviour is not an adequate approach to reach our goals. To dynamically observe or simulate a building's thermal properties a more complex approach is needed. Not only energy balance is needed, but also the changes in time.

Electro-Thermal Analogy

Electro-thermal analogy is a calculation method used in thermodynamics. The thermodynamical measures are put into electrical measures in order to run the calculations much easier. The same type of calculations are widely used by electricians.

Regarding the electro-thermal analogy, the temperature T or u [K] corresponds to the voltage and the heat q [kW] corresponds to the current of an electrical circuit. The thermal resistance R_{th} [K/kW] matches resistance. The very good property of the new approach is that capacitance is now in the game: called thermal capacity C_{th} [kWh/K]. This capacity causes some challenges at the design of the heating control.

There are three types of heat transfer. Conduction, convection and radiation. Convection transfers heat in liquid and gaseous media. Convection can be observed in the heating system of a building, or in the air of the room. Conduction occurs mainly in solid materials. Radiation is generated mainly by emitters or hot surface bodies.

A radiator in a room heats the surrounding by convection and by radiation. As the warmer air molecule reaches the wall, it gives its extra energy to the wall's particles. This is where conduction starts. A bunch of particles in the wall have increased temperature. Because of the diffusive property of the temperature this extra energy starts moving towards the colder particles.

This is conduction. Of course the larger the surface or the wall is, the bigger is this effect. And the thicker the wall is the smaller is this effect.

$$\frac{du}{dt} - \propto \Delta \mathrm{u} = 0$$

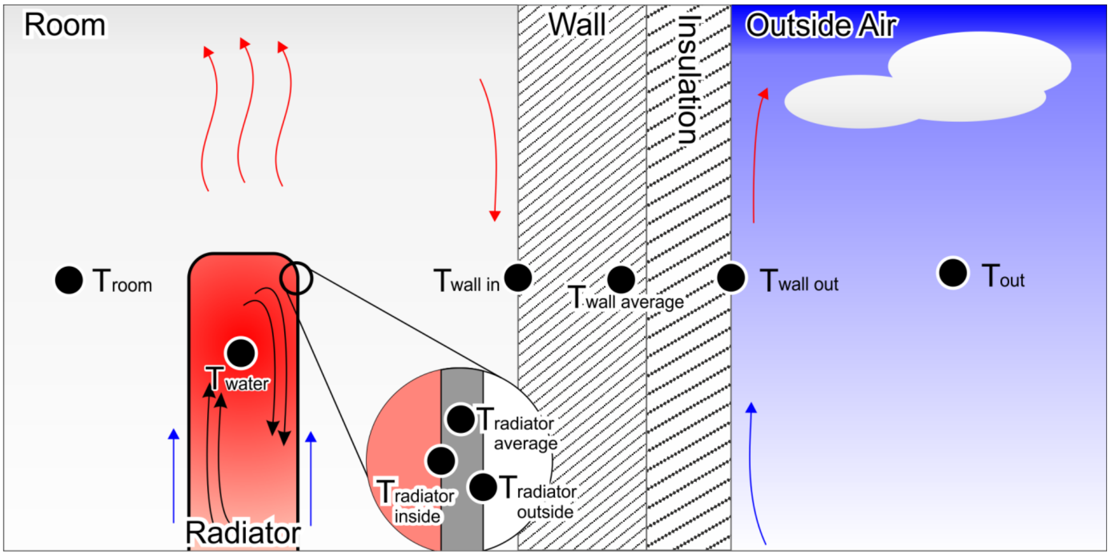
2. (Heat Equation)

Equation 2 tells that the greater the temperature difference between an arbitrary region of the material and its surrounding, the quicker is the heat transfer (conduction) from the region to its surrounding. α is thermal diffusivity. u is temperature.

$$\frac{du}{dt} - \propto \Delta \mathrm{u} - \frac{1}{c_p \rho} q = 0$$

3. (Extended Heat Equation)

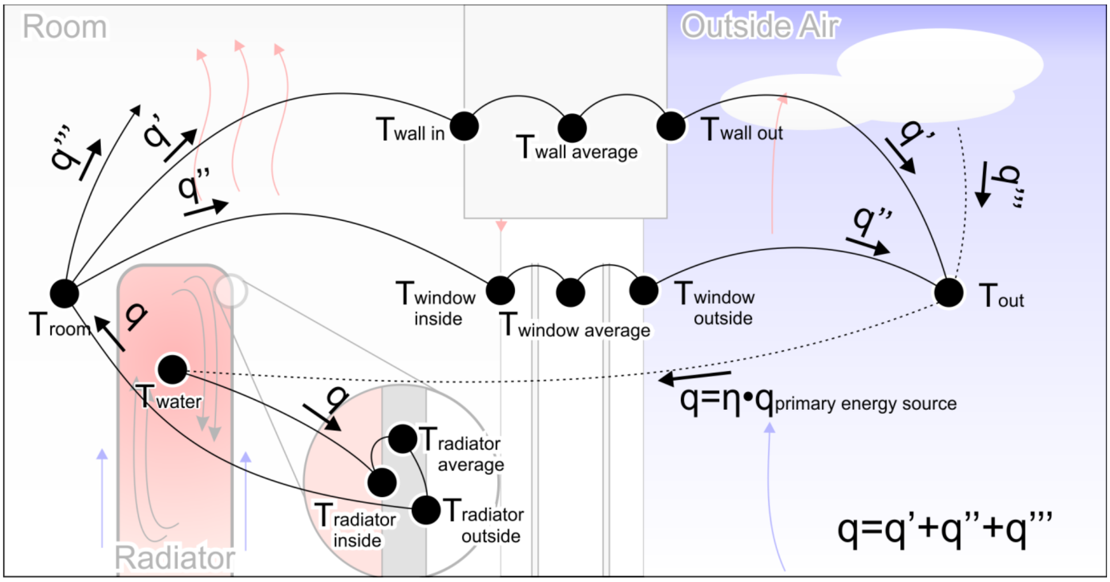
The extended heat transfer Equation 3 involves the effect of the continuous heating of heat generation. q is heat, ρ corresponds density and c_p is specific heat capacity.



10. Figure - Representation of Temperatures in a usual Thermodynamical System (György Barta, 2013)

Figure 11 shows the routes of the heat. q is the heat which increases the temperature in the room. All this heat goes out through the walls q’, the windows q’’ and through ventilation q’’’.

A unique thermal resistance value belongs to each q. To maintain a given temperature difference between the room and the surrounding, heat source is needed. So yes heat goes out definitely, but with its moving a beneficial temperature difference is created.



11. Figure - Representation of the Heat Flow in a common Thermodynamical System (György Barta, 2013)

Figure 11 can be transferred into a circuit diagram (Figure 12). On the picture q_2 is solar irradiation through windows, q_3 is solar gain through walls and q_{boiler} is the heat (power) of the boiler.

5.1.1.1 Thermal Resistance

Thermal resistance is an effect which slows and mitigates the limitless spreading of the heat. Thermal resistance can be defined in all three states of matter. Resistance is the reciprocal of the heat conduction.

Conduction is directly proportional to the heat and inversely proportional to the temperature difference. Conduction is a property of solid state materials.

For further invetigations the thermal resistance [K/kW] is introduced.

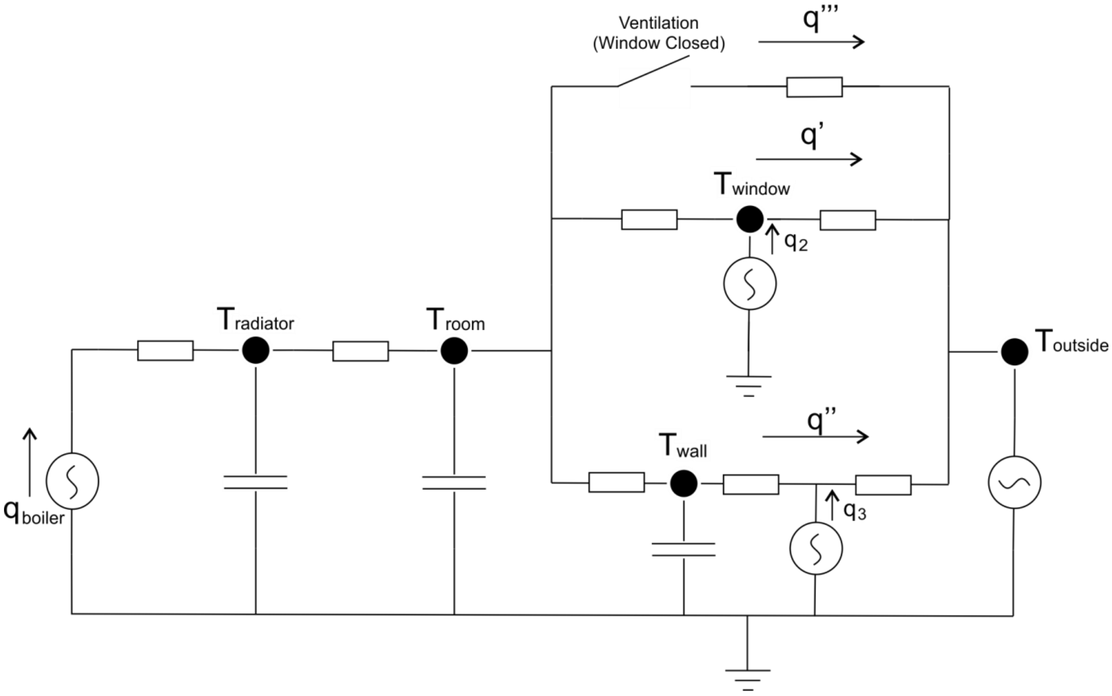
$$R_{th} = \frac{\overline{\Delta T}}{q}$$

4. (Calculation of R_{th})

Convection plays a significant role in liquid and gaseous media. Convection is non-linear.

Figure 12 represents an advanced thermodynamical model of a building or a room. The model is universal, because the same physical events occur in each observed case. The parameters vary depending on the scope, and type of the observation.

On Figure 12 the rectangles represent the thermal resistances. It is obvious that there are many. It is because the model is quite detailed. Many aspects are taken into consideration at the building of this model. Of course building up a perfect model is impossible, but working with a reasonable tolerance is feasible. For further tolerance details check: (García-Sanz 1997).



12. Figure – Temperatures in the Equivalent Circuit Diagram of the Thermodynamical Model of a Building (García-Sanz 1997)

The circles with vertical waves represent heat sources, the one with horizontal wave represents temperature source. The double horizontal line means thermal capacity.

5.1.1.2 *Thermal Capacity*

Thermal capacity C_{th} describes the heat storage of a body. When a body's thermal capacity is large than the body requires a lot of energy to be heated up. The unit of the thermal capacity is kJ/K or kWh/K.

On Figure 14 many thermal capacities can be found. Thermal capacity of the heating system means the overall capacity of the thermal liquid, the pipes and radiators.

Thinking of the thermal capacity of the air is surprising for the first time, but yes it is a notable factor. Thermal capacity of the air is not much, but there is a large volume of air in a building. The notable energy storage capacity of the air causes the energy loss during ventilation and opens the door for heat recovery ventilation systems.

$$q = C_{th} \cdot \frac{dT}{dt}$$

$$C_{th} = \frac{q}{\frac{dT}{dt}}$$

$$q = \frac{\overline{\Delta T}}{R_{th}}$$

$$\overline{\Delta T} = \overline{T_{in} - T_{out}} = \bar{T}_{in} - \bar{T}_{out}$$

$$dT = T_{in(t_n)} - T_{in(t_m)} \qquad m, n \in N^{+}$$

$$C_{th} = \frac{\frac{(\bar{T}_{in} - \bar{T}_{out})}{R_{th}}}{\frac{T_{in(t_n)} - T_{in(t_m)}}{t_n - t_{n-1}}} = \frac{(\bar{T}_{in} - \bar{T}_{out}) \cdot (t_n - t_m)}{R_{th} \cdot (T_{in(t_n)} - T_{in(t_m)})}$$

5. (Calculation of C_{th})

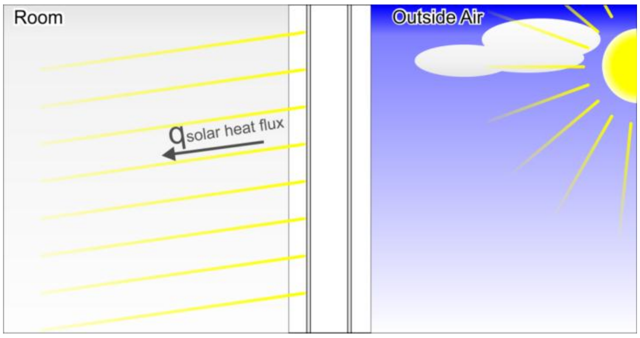
Thermal capacity of the wall is the most largest thermal capacity in a building and together with the thermal resistance of the wall they are the determinative properties of a building.

5.1.1.3 Heat

Heat q is the measure of the thermal flow. Unit is kW.

5.1.1.4 Solar Gain

Windows cause double effect on the buildings energy balance. On the one hand windows have lower thermal resistance than walls, this means more heat loss per square meter. On the other hand windows let sun beams through, this means even more kW of solar gain performance. In summer the extra heat is unwanted, but in the winter it is beneficial. The dimension of the solar gain is kW.

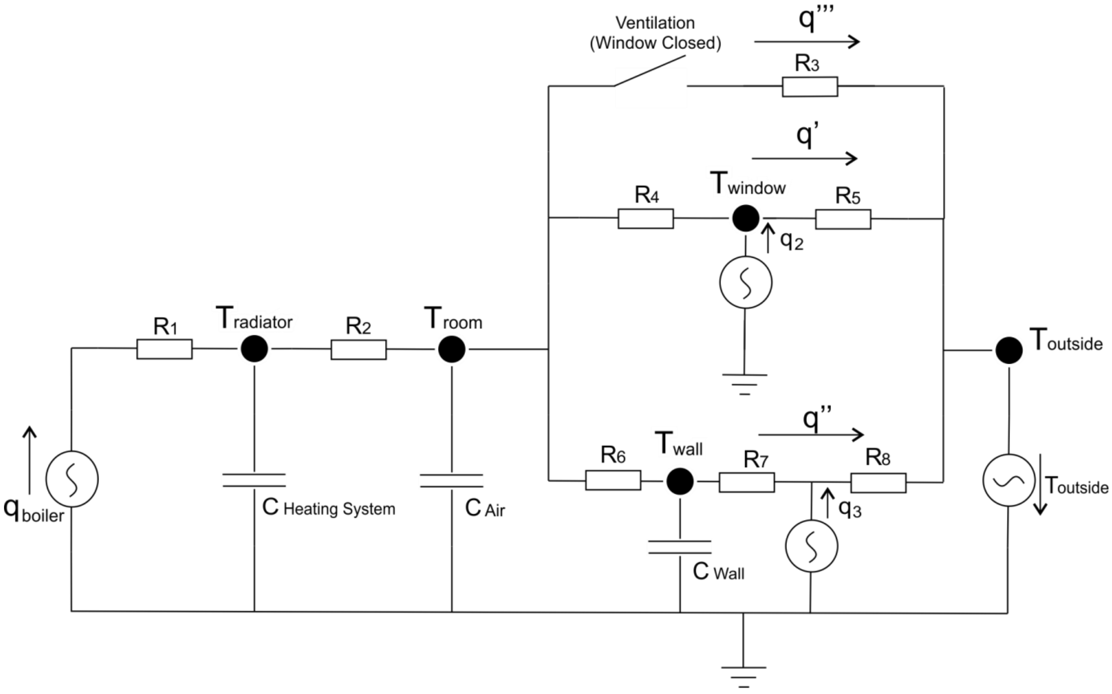


13. Figure - Representation of the Solar Gain through a Window (György Barta, 2013)

The direct 90° angle sunlight on the earth corresponds 1000 W/m^2.

5.1.1.5 Equivalent Circuit Diagram

A detailed circuit diagram (Figure 14) shows the passive and active circuit elements. The most influential parts of the system are R_7, R_8 -whom together represent the wall's insulation- and C_{wall} which represents the largest capacity within the house.



14. Figure - Equivalent Circuit Diagram of a common Thermodynamical System (García-Sanz 1997)

5.1.1.6 Dimensions Matching

The electro-thermal analogy calls for a translation of the measures and units. The units of the thermodynamic plane need to be fitted onto the units of the electric world. Table 1 shows the matched items.

While there is an electrical toolkit used for the thermodynamic simulations, at the parameterisation stage of a simulation only electric measures can be loaded into the model. The simulation runs as it was a real electric experiment, only the simulation result units have to be converted onto the thermodynamic plane regarding Table 1.

1. Table - Dimension Matching

Current [A]	Heat [kW]
Voltage [V]	Temperature [K]
Resistance [Ω]	Thermal Resistance [K/kW]
Power [W]	-
Capacity [F]	Heat Capacity [kWs/K=kJ/K]

Heat as a thermodynamic measure corresponds current in electricity. Temperature corresponds voltage. Capacity and resistance fit together in the two worlds.

With the created Table 1, now it is possible to load the right parameters into the model.

5.2 Modelling the COTIMO-concept

The model itself is the same as the one discussed in chapter 4. Three simulation is made for each of the following case studies.

The temperature data is 2012 imported from the database OPeNDAP (OPeNDAP 2008-2012).

Non-COTIMO full

Inner temperature regulated heating.

COTIMO home-type

Always occupied except workdays between 8 a.m. and 4 p.m.

COTIMO weekend-type

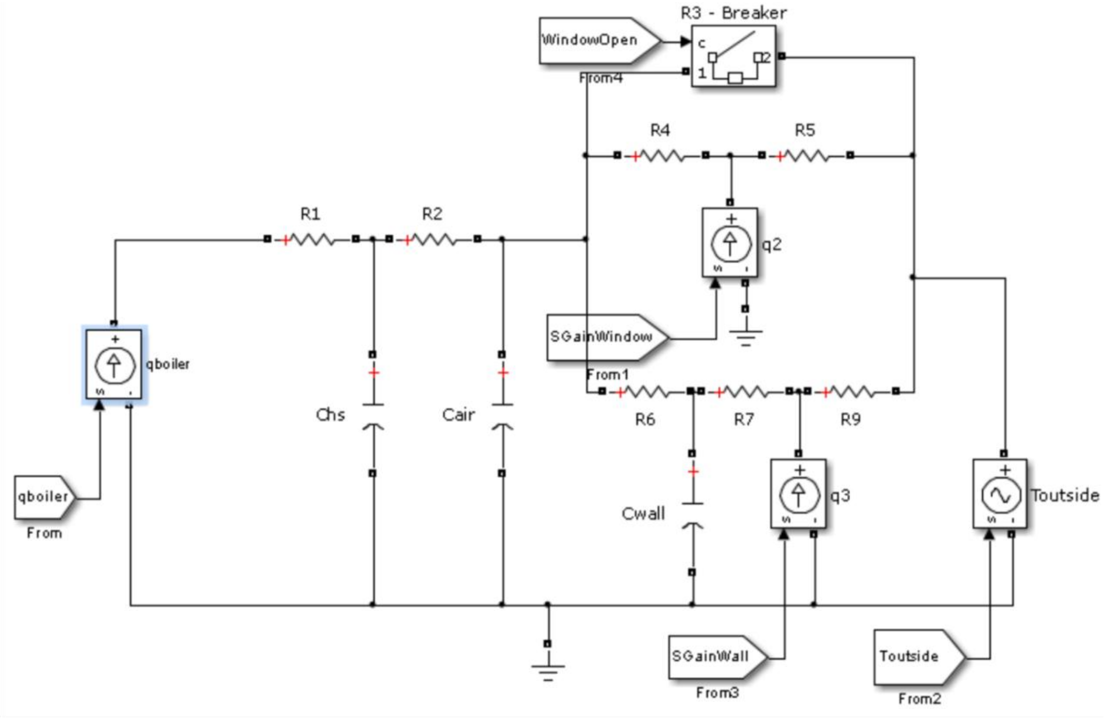
Occupancy starts at 4 p.m. Fridays and ends 12 p.m. Sundays.

COTIMO workplace-type

Occupied only on workdays from 8 a.m. to 4 p.m.

5.2.1 Simulation Setup: Apartment in Miskolc

Figure 15 is the model built up in Matlab Simulink. The model absolutely corresponds Figure 14. In the SimPower library there are pre-defined blocks like resistance, capacitor, current source and so on.



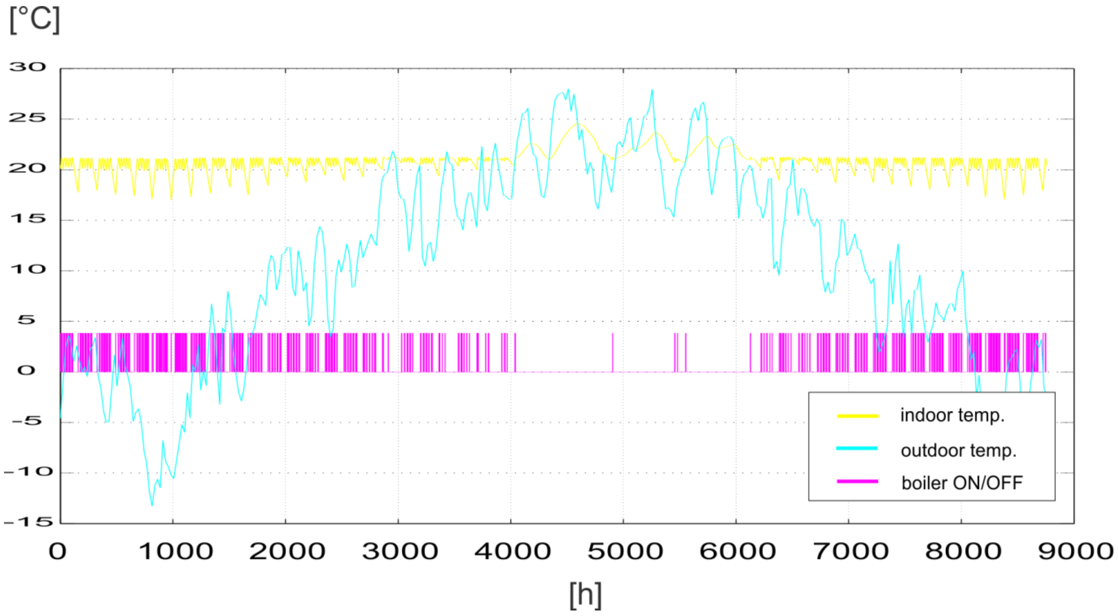
15. Figure - Matlab Simulink Based Thermodynamical Model of a Building (García-Sanz 1997)

To make the simulations easy and comparable during the simulation the windows are closed and there are no solar gains.

5.2.2 Simulation Results

Figure 16 shows the simulation results of an apartment in Miskolc, Hungary. The control is workplace-type COTIMO. The indoor temperature curve (yellow) shows decrease on the weekends.

The indoor temperature reaches deeper temperature values on weekends in the winter, less in the spring and autumn. In summer the inside temperature increases up to 25 °C.



16. Figure - Workplace-type COTIMO Driven Heating Control in the Apartment in Miskolc (György Barta, 2013)

Table 2 is a simulation report. Occupancy means the type of the simulation described in chapter 4.2. The simulation result represents the whole-year consumption of the building for heating. Consumption change shows the extra energy consumed with the given control. Minus consumption change means saving. Reference for the comparisons is the non-COTIMO classic control.

2. Table - Simulation Schedule in Miskolc (György Barta, 2013)

sim nr.	thermal resistance [k/kW]	thermal capacity [kWh/K]	occupancy	simulation result / energy used [kWh]	consump-tion change	type of ctrl
I.	15,62	15,366	full	5922,50		classic
II.	15,62	15,366	home-type	5930,90	0,14%	COTIMO
III.	15,62	15,366	weekendhouse-type	5262,50	-11,14%	COTIMO
IV.	15,62	15,366	workplace-type	5681,20	-4,07%	COTIMO

5.2.3 Energy Saving Potential

According to Table 2 the only remarkable saving appears at the weekendhouse-type control. This is 11,24% saving. It is very interesting, that at the home-type occupancy simulation an increase came out. This means, it is better to keep a constant temperature than control it with high fluctuations of reference temperature setting.

6 Experiments

In this chapter three measurements and nine simulations are introduced. Three simulations are already presented in the chapter 5.2. In all the three buildings first of all the measurements were described and demonstrated, and after with the help of the measurement results simulations are performed. One apartment, one resort and one hotel is described in this chapter.

6.1 Experiment 1: Apartment in Miskolc

Miskolc is town in North East Hungary. The author lives there. The apartment itself is in a newly built multiple-dwelling building. The building fulfils the requirements of the present day, so the windows and the walls are insulated. The apartments in the building are fairly economic.

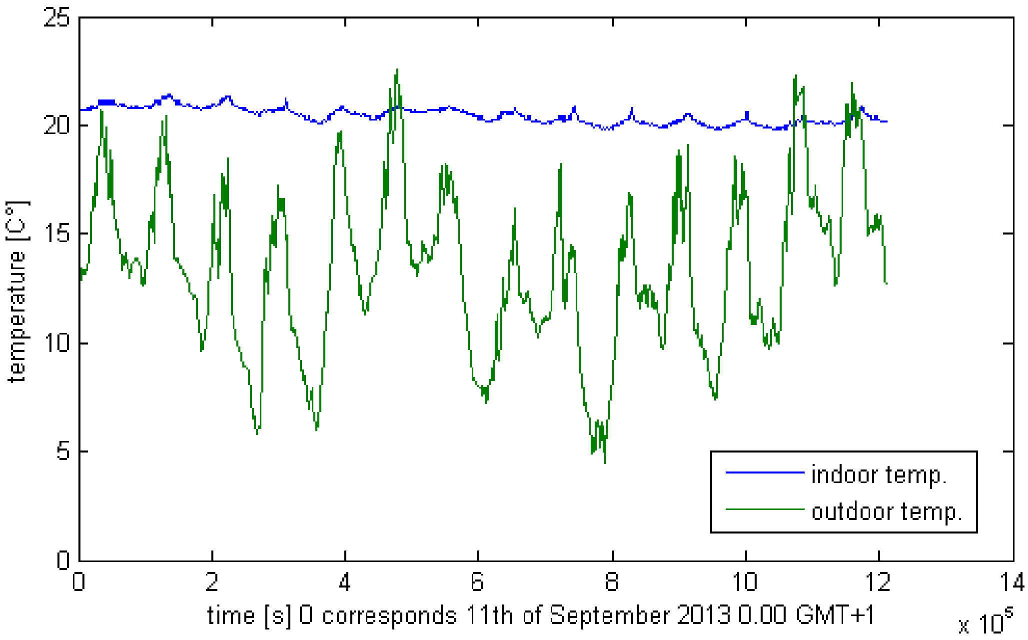
6.1.1 Measurement Setup

The observed room is in a new multiple-dwelling building on the ground floor. One of the room’s walls is an inside-outside wall, the other ones are all inside-inside walls. The room was unused during the measurements. The function of the apartment is home-type.

The measurement setup is very easy indeed. One temperature meter inside, and one outside. When positioning the outside temperature meter always place it into a whole day shade. Direct sunlight can cause extremely increased temperature values.

6.1.2 Collected Data

The measurement took place from the 11th of September 2013 0.00 GMT+1 to the 25th of September 2013 0.00 GMT+1. See Figure 17.



17. Figure - Result Diagram of a 2 Weeks Long Measurement in Miskolc (György Barta, 2013)

The green line represents the outside temperature. The blue line is the indoor temperature. It is obvious, that the peaks at both lines in the daytime, and the valleys are at night-time.

3. Table - Thermal Resistance Measurement in Miskolc (György Barta, 2013)

first sec [s]	last sec [s]	thermal resistance [K/kW]
231600	268800	15,18
322800	368400	13,81
488400	532200	17,20
750000	807000	16,30
avg		15,62

The outside temperature fluctuates between 5 °C and 22 °C this is not surprising considering that the measurements were done in September. The indoor temperature shows a slight decrease during the two weeks of measurement. This is due to the thermostat control setting. The thermostat was set to 20 ˇC so the boiler did not start to heat during the simulation.

Looking at the inside temperature on Figure 17 there are “hills” and “valleys” to observe. As mentioned hills occur daytime and valleys occur in the nighttime. On many hills there are small, but intense peaks visible. These fast temperature jumps occur because direct sunlight radiates into the room during that short period of time.

6.1.3 Measurement Results

Equation 4 is used to calculate the thermal resistance. The calculation is done with arithmetic mean values. So the temperature differences ∆T are calculated with mean inside temperatures and mean outside temperatures.

4. Table- Thermal Capacity Measurement in Miskolc (György Barta, 2013)

first sec [s]	last sec [s]	temp difference [K]	time difference [s]	indoor temp change [K]	thermal capacity [kWh/K]
145800	184800	8,39	39000	0,4	14,549
231600	270600	12,24	39000	0,5	16,985
317400	357600	11,75	40200	0,5	16,801
400800	442200	7,13	41400	0,4	13,130
avg					15,366

Looking at the Table 3, the result for the thermal resistance is 15,62 k/kW. This could seem too low, but it is not surprising, because the apartment is in a multiple-dwelling building, and it has only two walls to the outside.

Table 4 provides the calculated thermal capacity values. Equation 5 is used for the calculations. The capacity of the apartment is 15,37 kWh/K in average. This means 15,37 kWh energy is needed to heat up the apartment by 1 °C.

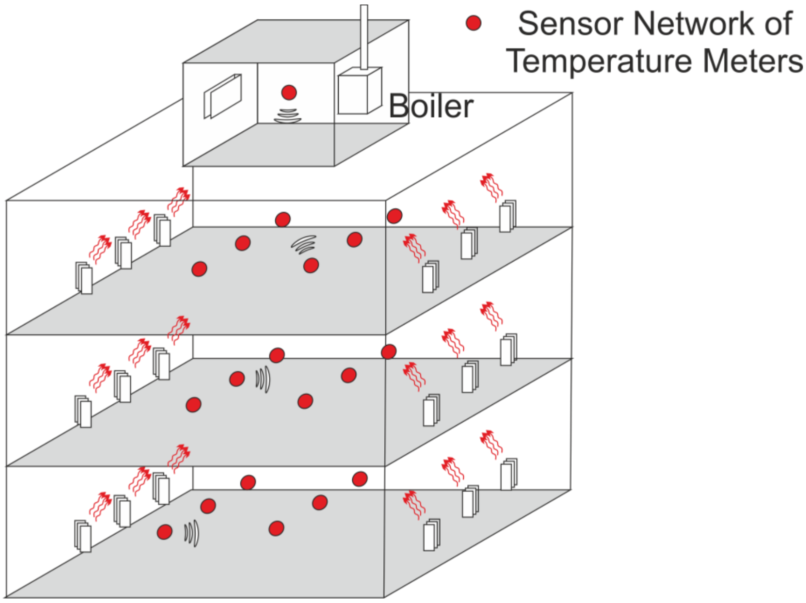
6.2 Experiment 2: Hotel Lilla

Hotel Lilla is located in Balatonszemes at the lake Balaton. The leverage effect of the huge lake is appreciable on the measured outside temperature data (Figure 19). The leverage effect of the lake causes a close-to-zero temperature during the winter. Zero degrees in February counts quite mild compared to other regions in Hungary on the same latitude. Hotel Lilla is a four storey building.

6.2.1 Measurement Setup

The hotel is open only in the summertime. In the winter an anti-freezing system keeps the indoor temperature higher than 4 °C. Because different parts of the building have different temperatures, an adaptive and distributed control is used.

The coldest parts of the building are the top-corner apartments. The warmer ones are on the ground floor. Top corner apartments are ap.13 and ap.14. See Figure 19. Ap. 1, ap. 2, ap. 3, ap. 4 and ap. 5 are on the ground floor.



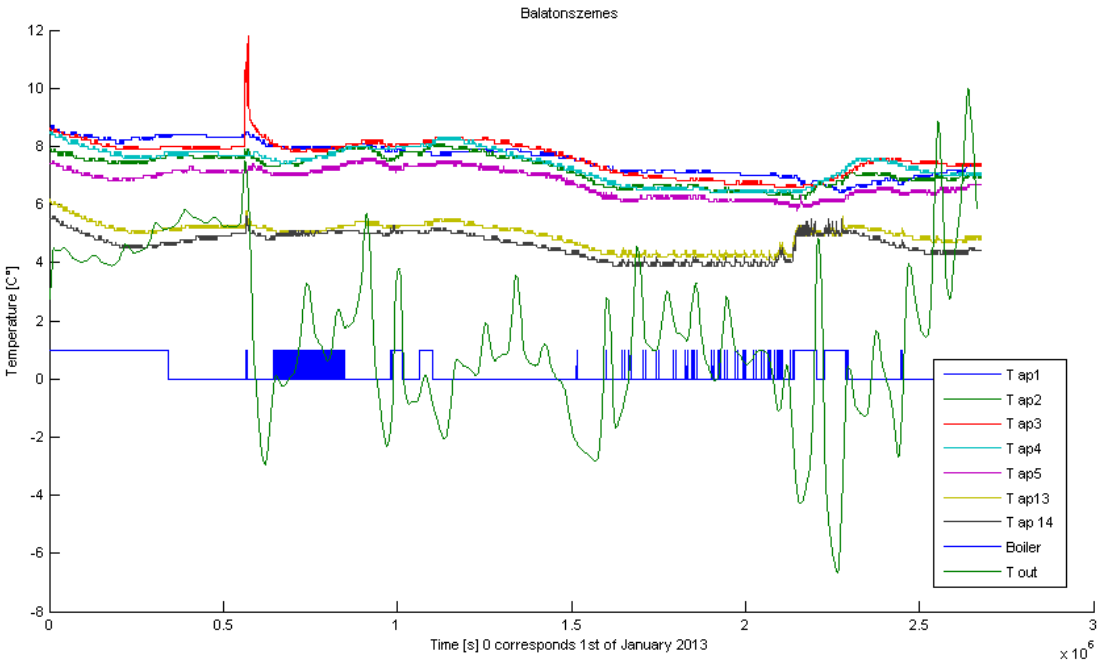
18. Figure - Thermostat Locations in Balatonszemes (György Barta, 2013)

The hotel has only one boiler, but in each apartment there is a thermostat and the radiators are individually controllable. The thermostats can directly give commands to the adjustable valves, but on the other hand they are also nodes of a mesh network Figure 18.

As the thermostats are part of a network; there measured data can be collected, and visualized. See Figure 19.

6.2.2 Collected Data

As described above, the temperature values are low due to an anti-freezing system. The measurements took place from the 1st of January 2013 0.00 GMT+1 to the 1st of February 0.00 GMT+1.



19. Figure - Results of a One Month Measurement in Balatonszemes (György Barta, 2013)

The outside temperature curve had to be filtered, because in certain times of a day it received direct sunlight causing unwanted outside temperature extremes.

Adequate intervals of the diagram for thermal resistance metering are the constant inside temperature intervals. The energy pumped in have to cover the energy outflow. This is the basis of the calculation.

It is clearly visible, that during periods of no boiler activity the inside temperature decreases. In the first 400 h the data is unreliable due to maintenance of the monitoring system

6.2.3 Measurement Results

After a couple of measurements the thermal resistance turned to be around 0,916 K/kWh. This value used to be much higher, but in 2010 a refurbishment took place, so the walls got insulation and the windows got replaced.

5. Table - Thermal Resistance Measurement in Balatonszemes (György Barta, 2013)

first sec [s]	last sec [s]	thermal resistance [K/kW]
684000	785400	0,580
1043400	1235400	1,400
637800	1197000	0,921
682200	754800	0,690
2155200	2555400	0,940
2155200	2634000	0,955
2155200	2663400	0,926
avg		0,916

The thermal capacity value is 1022,97 kWh/K. This is extremely high compared to the size of the building. This is due to the construction technology of the house. The house was built in 1968.

6. Table - Thermal Capacity Measurement in Balatonszemes (György Barta, 2013)

first sec [s]	last sec [s]	temp difference [K]	time difference [s]	indoor temp change [K]	Thermal Capacity [kWh/K]
1191000	1574400	6,019	383400	0,85	837,96
1191000	1402200	5,384	211200	0,325	1079,86
1191000	1345200	5,676	154200	0,15	1801,04
1345200	1536000	5,819	190800	0,5	685,33
1369200	1564200	6,494	195000	0,55	710,65
avg					1022,97

In 1968 in Hungary there was socialism. In that era concrete, iron and gasoline were really cheap. Due to the facts the mass of the building is 5 times higher than a usual building built up today.

6.2.4 Simulation Setup

During the following simulations the thermal resistance is set to 0,916 K/kWh, thermal capacity to 1022,97 kWh/K.

To make the simulations easy and comparable during the simulation, the windows are closed and there are no solar gains.

6.2.5 Simulation Results

Table 7 demonstrates the simulation results of the building. Simulation Nr. III. shows the largest saving among the simulations. This is weekendhouse-type COTIMO again. In case of high frequency occupancy changes the consumption increases again as we saw at the simulations of the Apartment in Miskolc.

7. Table - Simulation Schedule in Balatonszemes (György Barta, 2013)

sim nr.	thermal resistance [k/kW]	thermal capacity [kWh/K]	occupancy	simulation result / energy used [kWh]	consump-tion change	type of control
I.	0,916	1022,97	full	101 473,79		classic
II.	0,916	1022,97	home-type	101 986,89	0,51%	COTIMO
III.	0,916	1022,97	weekendhouse-type	95 305,68	-6,08%	COTIMO
IV.	0,916	1022,97	workplace-type	98 908,30	-2,53%	COTIMO

After two simulations two tendencies start to unfold. One is that the highest saving is achieved at the weekendhouse-type simulations. This is an expected result, because weekendhouse-type usage of a building means rare occupancy. The other tendency is that home-type simulations increase the consumption instead of reducing it.

6.2.6 Energy Saving Potential

Having very high thermal capacity the potential of savings is very low. High capacity means slow cool down regarding the exponential decay (see Equation 6).

$$u_{(t)} = U \cdot e^{-\frac{t}{R_{th}C_{th}}} \qquad \text{6. (Temperature Decay)}$$

In the above equation U is the temperature difference, it corresponds ∆T . With the equation it is easy to conclude that high R_{th} and/or C_{th} values cause a slow indoor temperature ($u_{(t)}$) decrease. Slow indoor temperature decrease causes high mean indoor temperatures.

In case the mean indoor temperature is not significantly lower than used to, there is no significant saving. Low R_{th} and/or C_{th} values help the concept to be successful, with other words: with low R_{th} and/or C_{th} values, higher savings are achievable.

6.3 Experiment 3: Resort in Szilvásvárad

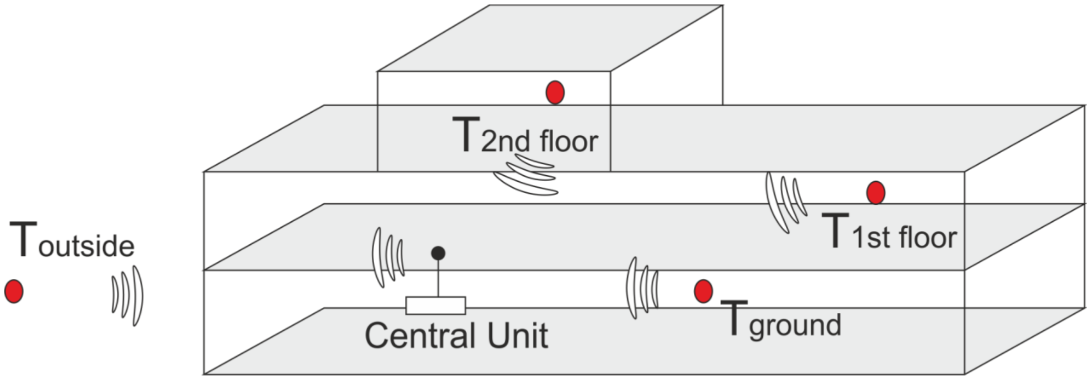
The resort in Szilvásvárad is a 1000 m^2 building with an 8 kWp PV system installed on the rooftop. The building has good insulation and heat recovery ventilation system provides economic fresh air. The resort is equipped with two boilers; a biomass boiler and a natural gas boiler. The building is new. The building was finished in 2012.

6.3.1 Measurement Setup

The facility has an advanced heating. The data required to run the measurements and simulations can be extracted out of the installed monitoring and control system. There are thermostats located on each floor of the three storey building. There is one outside temperature meter as well.

Figure 20 demonstrates the location of the thermometers inside and outside of the building. The indoor thermometers are placed in living spaces. On the ground floor the thermometer is in the occasion room. On the first floor the thermometer is located in a guest room. On the third floor the thermometer is placed in the master suite.

The building has floor and wall heating. Each room is a zone, and the flow rate is adjustable in each zone. So each zone has a valve which has to be set properly in order to reach a homogeneous temperature distribution in the building. The setup or the fine-tuning of the building's heating system is a long procedure, because of the thermal properties of the building. The building has very good insulation, so the cool down time and the heat up time are long. A change at the zone's valve performs its impact in a day or more. This duration is of course dependent on the outdoor temperature as well.



20. Figure - Thermostat Locations in the Resort in Szilvásvárad (György Barta, 2013)

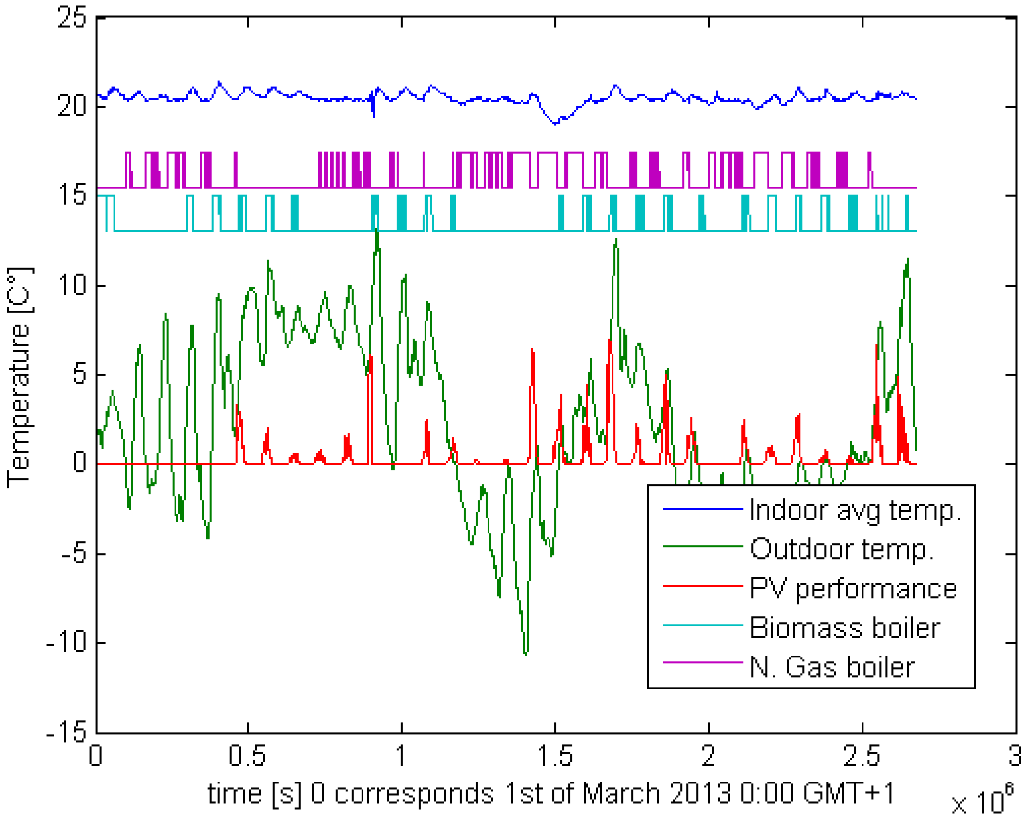
As mentioned before the resort has two boilers. A biomass and a natural gas boiler. An advanced control was developed for the building to run the two boilers properly. Important requirement was that in case of firing in the biomass boiler the control system stops the natural gas boiler, and starts circulating the warm water out of the biomass boiler into the house. In case the firing stops, the control system switches back to the natural gas system.

6.3.2 Collected Data

On Figure 21 not all the temperature data, but only the average temperature is presented. The house has two boilers so both are represented. For a curiosity the PV system's performance is also shown. It is useful in our case to be able to ignore the effects of solar irradiation. Ignoring sunlight is helpful, because now the focus is really on the thermal resistance, and thermal capacity.

It is interesting to see, that there is a time shift between the PV peak and the outside temperature peak. This is due to the two facts. One is that the temperature is proportional not with the solar radiation, but its integrated form. The other fact is that the roof of the PV instalment is oriented to the South East.

The measurement starts on the 1st of March 2013 0.00 a.m. GMT+1, ends on the 1st of April 2013 0.00 a.m. GMT+1.



21. Figure - Results of a One Month Long Measurement in Szilvásvárad (György Barta, 2013)

The scale on the y axis works also for the PV performance. The PV system is a 8 kWp system. It is visible on Figure 8, that there are some really good PV performances during the month of observation. In each and every case a good PV day is followed by a good outside temperature increase.

6.3.3 Measurement Results

The thermal capacity turned out to be 1,82 K/kW. It means that 1 kW heat generated in the building causes 1,82 °C temperature difference. This value compared to the size of the house is high enough to say that the building has good thermal resistance even though the resort has an energetically unfavourable geometry.

Table 8 shows the measurement results. The resistance results are close to each other.

8. Table - Measurement of the Thermal Resistance in Szilvásvárad (György Barta, 2013)

first sec [s]	last sec [s]	thermal resistance [K/kW]
180000	297600	1,873
750000	885000	1,952
1224000	1380000	1,715
1986000	2099400	1,737
avg		1,820

The thermal capacity is 191,73 kWh/K. The size of the resort is nearly equal to the Hotel Lilla described in chapter 5.2, but the thermal capacity is only one fifth of the hotel's. Thanks to the development of the construction technology, much less material is needed to build up buildings with more favourable thermal properties.

9. Table - Thermal Capacity Measurement in Szilvásvárad (György Barta, 2013)

first sec [s]	last sec [s]	temp difference [K]	time difference [s]	indoor temp change [K]	thermal capacity [kWh/K]
426000	453000	16,06	27000	0,367	180,50
502800	550800	12,72	48000	0,533	174,82
595200	635400	13,04	40200	0,367	218,29
1126200	1148400	17,16	22200	0,300	193,89
666000	699000	13,09	33000	0,367	179,83
2488200	2521200	20,15	33000	0,500	203,05
avg					191,73

6.3.4 Simulation Setup

During the following simulations the thermal resistance is set to 1,82 K/kWh. Thermal capacity 191,73 kWh/K. To make the simulations easy and comparable during the simulation the windows are closed and there are no solar gains.

6.3.5 Simulation Results

Table 10 shows that the highest saving achieved at the Resort in Szilvásvarad is 8,52%. The results show that the only significant saving potential is at rare temperature adjustments. Rare temperature adjustment is also called low frequency occupancy change.

10. Table - Simulation Schedule in Szilvásvárad (György Barta, 2013)

sim nr.	thermal resistance [k/kW]	thermal capacity [kWh/K]	occupancy	simulation result / energy used [kWh]	consump-tion change	type of control
I.	1,82	191,73	full	50923,07		classic
II.	1,82	191,73	home-type	50967,03	0,09%	COTIMO
III.	1,82	191,73	weekendhouse-type	46582,41	-8,52%	COTIMO
IV.	1,82	191,73	workplace-type	48659,34	-4,45%	COTIMO

6.3.6 Energy Saving Potential

The COTIMO concept in the resort has obviously low saving potential. The good insulation lets no space for this kind of EE measure.

7 Evaluation of the Results of the Experiments

In this chapter the experiment results are examined for further findings. Table 11 and Table 12 compare the buildings to highlight deeper correlations. After that rules of thumb get defined in order to help specialist distinguishing good sites of implementation from bad sites of implementation.

7.1 Results Comparison and Analysis

Table 11 contains each simulation results. The worst result among all occurs at the home-type usage simulation in the Hotel Balatonszemes. Worst result means that COTIMO control not even made saving, but it increased the consumption of the building. There is a surplus at home-type usage in each observed buildings.This means that COTIMO at high frequency occupancy change results a consumption surplus.

The highest saving among the simulations occurred in the Apartment in Miskolc at weekendhouse-type usage. The value is 11,14% saving. COTIMO at weekendhouse-type usage gave the best results for each building. Workplace-type usage gave results from 2,5 % saving to 4,5 % savings.

11. Table - Simulation Results Comparison (György Barta, 2013)

	full	home-type	weekendhouse-type	workplace-type
Apartment in Miskolc	0%	0,14%	-11,14%	-4,07%
Hotel in Balatonszemes	0%	0,51%	-6,08%	-2,53%
Resort in Szilvásvárad	0%	0,09%	-8,52%	-4,45%

It is very interesting that the Resort in Szilvasvarad is more sensitive on COTIMO if workplace-type used, than the Apartment in Miskolc. At weekendhouse-type usage vica versa: Apartment in Miskolc is more sensitive than the Resort in Szilvásvárad. This means that the buildings react more sensitive in some frequency domains than in others.

To answer this phenomenon we have to go quiet deep into the topic of system theory. Buildings are Linear Time-Invariant (LTI) systems. Systems have transfer functions. Transfer functions can be calculated out of the building's parameters such as R_{th}, C_{th}. When a system is excited by a signal it gives a response. Now presence (see chapter 4.1.1) is the excitation signal, and inside temperature is the response. While each building has a different transfer function the responses differ as well. Apartment in Miskolc gives "lower inside temperature response" at a low frequency occupancy change than Resort in Szilvásvárad.

For middle frequency occupancy change Resort in Szilvásvárad answers with "lower inside temperature response" than Apartment in Miskolc. "Lower inside temperature response" also means higher savings, because the difference between inside and outside temperature is higher.

12. Table - RC time Constants (György Barta, 2013)

	Rth*Cth [h]
Apartment in Miskolc	240,02
Hotel in Balatonszemes	937,04
Resort in Szilvásvárad	348,95

At the comparison of the different types of simulations, the weekendhouse-type usage of a building seems to earn the highest savings. /This type of simulation may be not realistic, because status quo for weekendhouses may not be full time heating/. Weekendhouse-type means low frequency occupancy change. At low frequency occupancy change the cooling times are longer. This means a lower mean inside temperature. Lower mean inside temperature means higher savings. Check equation 6 for the dynamics.

In case high frequency occupancy change the cooling terms are shorter, so the inside mean temperature decreases only a bit, which means there is a tiny energy saved. More consumption is also possible (see Table 11). The reason behind is the regulation, namely overregulation of the temperature. For high frequency occupancy change at the end we get higher mean inside temperature than in case no COTIMO used. Higher mean inside temperature means more consumption.

As Equation 6 describes the dynamics of cooling, it is obvious that a high $R_{th}C_{th}$ product means slow cool down. Slow cool down means higher mean inside temperature. Higher mean inside temperature means less saving.

Table 12 presents the RC time constants. Let us observe the Hotel in Balatonszemes which really has high RC time constant. Table 11 makes it obvious that it occurred the least saving among all buildings at the Hotel in Balatonszemes. So this theory works in this case. Don't expect too much when a building or apartment has high RC time constant.

In each point of a building regardless in a small room or in a big hall one thermodynamical constant is the same. It is the RC time constant. Why is that same everywhere? Let's observe an arbitrary space in a building. Is it small? The space has a high thermal resistance. Is it large? The space is having a low thermal resistance. A small space has a little surface where smaller amount of energy can be transported. A large space has large surface where energy transport is more intense. Regardless what the space is filled with, this theory works.

Thermal capacity works in the other direction. A small space has low thermal capacity; a large space has high thermal capacity. The discussed properties of R_{th} and C_{th} cause that their product is the same in a building regardless the size of the observed space.

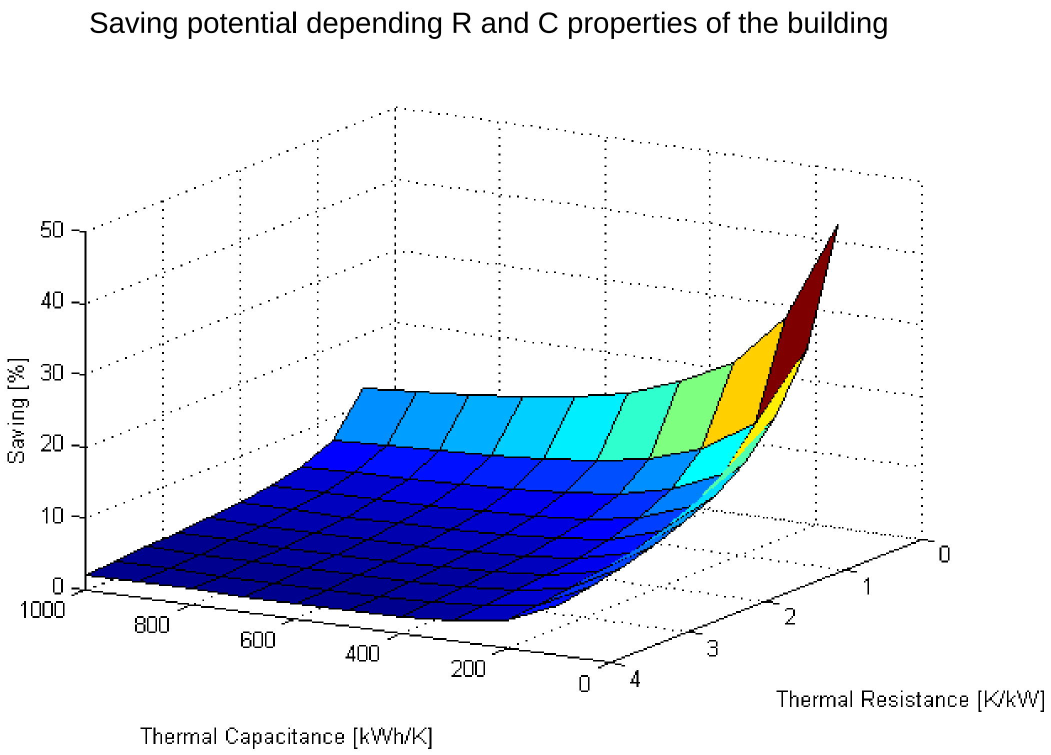
This constant is a building specific constant, and probably the most talkative constant among all. As mentioned before this constant determines the cooling time of a building, a room, or a zone.

7.2 Practical Energy Efficiency Potential of the COTIMO-concept

Figure 22 is created out of 200 simulations. One hundred classic control type and one hundred COTIMO weekendhouse-type simulation took place. The result shown below is calculated with the equation 8.

Figure 22 shows a very clear connection between R_{th}, C_{th}, and the achieved saving. The above mentioned property that high RC time constants reduce saving seem to be confirmed. The figure does not portray the connection between frequency of occupancy change and the saving. Best savings can be achieved at low RC time constants not considering the type of usage of the building.

Figure 22 tells also that low thermal capacity buildings are interesting at any insulation. These are wooden houses for example. Buildings with low thermal resistance are also interesting at any type of construction material. These type of buildings are for example bad geometry buildings (energetically), historic buildings where no insulation is allowed.



22. Figure - Representation of the Saving Depending on the Thermal Resistance and the Thermal Capacity (György Barta, 2013)

It turned out that high $R_{th}C_{th}$ product kills the concept. High frequency fluctuations kill it also. There has to be some rules of thumb to approximately locate the adaptability of the concept.

For further investigation Shortest Cooling Term (SCT) is introduced. This simple means the minimum number of cooling hours.

$$SCT \geq \frac{R_{th}C_{th}}{4}$$

7. ("worth to install" rule)

Equation 6 presents the dynamics of cooling. The lecture of the equation is that the $R_{th}C_{th}$ product determines the speed of cooling. In case the $R_{th}C_{th}$ product is big the SCT can still be big enough to present some sort of saving. In the other case $R_{th}C_{th}$ product is low; there is a high possibility of having right potential saving potential.

$$Saving = \frac{f_{classic}(R_{th}C_{th}, \Delta T) - f_{COTIMO}(R_{th}C_{th}, \Delta T, SCT)}{f_{classic}(R_{th}C_{th}, \Delta T)}$$

8. (Equation for Saving)

The saving is definitely a function of the $R_{th}C_{th}$ product, ∆T and SCT. Further investigation is required to give an exact figure for the calculation of the saving.

7.3 Literature Comparison

Studies and pilot projects for testing the intelligent HVAC control report also the same dimension of savings:

“Whole-house conditioning consumed 20.5% more energy than our prototype implementation of room-level zoning, on average (Tamim Sookoor 2013)”.

“Recent studies showed that commercial buildings could reduce energy usage between 15% and 40% by closer monitoring and managing its energy usage (Yahia Tachwali 2007)”.

“With an implementation using commercial off-the-shelf (COTS) components and a simple control algorithm we demonstrate an almost 15% energy saving in a residence over its existing centralized thermostat (Whitehouse, RoomZoner: Occupancy-based Room-Level Zoning of a 2013)”.

7.4 Determining Target Market

Interesting are buildings having low RC time constants and/or being rarely visited. Huge ∆T is also attractive. Huge rooms, even conference rooms, halls are very interesting indeed because they have comparable investment cost to smaller rooms, but the energy saved is much more.

Cinemas, conference centres, weekend houses, university auditoriums, schools, sport halls, churches, any kind of bad insulated, bad geometry buildings are motivating targets. Bad insulated old buildings are interesting. Even rooms or buildings where higher temperature is needed, therefore ∆T is increased so saving increase. Glass office buildings are interesting as well, while bad wall insulation.

Very good niche market can be the category of historic buildings, where no facade renovation is permitted. Owners of such buildings would possibly invest in such an EE measure.

Private, industrial, governmental clients need to know about the concept mostly those who use old real estates and have a limited budget to heat them, to maintain them, or even to refurbish them. Owners of historic buildings also seem to be potential buyers of the concept.

8 Conclusion

Before this work. the concept was an idea with rough estimations of achievable savings. With a basic knowledge of thermodynamic behaviour of a buildings - indoor temperature response to an always changing target temperature- could be estimated.

The results of this paper reach the bottom level of the expectations from almost all aspects, but never the less they approached the expectations. Many lessons are learnt for example being careful with saving estimates, because savings depend on many factors. Not taking into consideration all factors, easily lead to incorrect estimates.

There is a literature dealing with this topic. The papers are new from 2012 and 2013. It means this work is written at the very beginning of a new research area.

There are some really great experts on the field, namely Tamim Sookoor and Kamin Whitehouse. They are authors or co-authors of many papers listed in the Bibliography. Both work on the University of Virginia. They represent now the cutting edge of the involved field.

All together three long duration thermal property measurements were performed in this work. The buildings showed quite different thermal nature, although it was not a representative sampling.

In the COTIMO concept occupancy sensors or motion detectors detect occupancy in a room or zone. A server processes the gained data and tries to set up trends. The control system regulates the temperature in a room according to its predicted occupancy.

Twelve COTIMO simulations were performed in order to unveil the concept's potential.

The biggest lecture of the paper is that the achievable saving is a function of the thermal resistance, the thermal capacity and the frequency of the use of the building. The concept works best at buildings with low RC time constants and at low frequency occupancy changes.

The simulations resulted saving values between 2% and 12%. This domain is coherent with other papers found in the literature. It is not recommended to install the system in case of high frequency occupancy changes. In such cases the building's heat consumption may be higher than without the system.

Knowing the bottlenecks of a technology lets the specialist be more conscious to choose the potential sites of good saving. Where is a good saving there is a good money, this is an inherent property of a win-win scenario.

In each case before installation measurements and planning are needed. Simulations have to be part of the planning procedure as well. Rules of thumb are provided to make an initial estimation the worthiness of installing COTIMO. Fortunately no licensing procedure is necessary to implement such a system.

As one of the core objectives of this work was to develop a model where different energy efficiency measures can be simulated; the model was built and introduced. Now there is a proper toolkit to investigate on every potential sites of application. The model is ready to investigate in a wide range of potential sites.

Rules of thumb created with the help of the simulations. These rules can give a rough estimation to a specialist whether to start thinking in COTIMO or not without running a more complex simulation.

Cyber security has to be taken seriously. Such a cyber-physical system can cause huge losses in case an unauthorized body takes control. Secure operation technology is achievable even in case of remote control. Once the system is installed, configurations, updates and surveillance can be done with remote access, this means there is no need to visit the place. Deeper interventions may be done on-site.

The investment cost of the implementation of an advanced energy monitoring and control system varies. Customised solutions are well fitted to the needs, but require experts and many working hours to develop and test the system. Customised solutions are more expensive.

Commercial solutions are easy to implement, and they are also robust, but a high level synthesis of the different type of devices is rarely achievable. These systems are cheaper.

Private, industrial, governmental clients need to know about the concept mostly those who use old real estates and have a limited budget to heat them, to maintain them, or to refurbish them. Owners of historic buildings also seem to be potential buyers of the concept.

The COTIMO concept and the intelligent energy use in general may be very promising fields. The COTIMO concept showed its strengths but also its weaknesses. The work did not give a representative picture because all the observed buildings were newly built or refurbished. Energy consciousness today causes good insulation of the buildings which means low adaptability of the system.

Bibliography

2008-2012. http://www.opendap.org (accessed 07 15, 2013).

Chang-Sic Choi, Jinsoo Han, Wan-Ki Park, Youn-Kwae Jeong, Il-Woo Lee. *PROACTIVE ENERGY MANAGEMENT SYSTEM.* IEEE 15th International Symposium on Consumer Electronics. 2011.

DLNA Connect and Enjoy. 2013. www.dlna.org (accessed 11 17, 2013).

García-Sanz, M. *A reduced model of central heating systems as a realistic scenario for analyzing control strategies.* Elsevier Science Inc., 1997.

Haas, Reinhard. *Introduction to energy systems and the relevance of renewables.* Performed by Reinhard Haas. Reinhard Haas, Vienna. October 2010.

HomeMatic. *HomeMatic.* 2013. www.homematic.com (accessed October 31., 2013).

Johnson Controls. *J. Controls.* Johnson Controls. 2013. www.johnsoncontrols.com (accessed October 31., 2013).

Klemport, Oliver. "Wohlfühltest für Gebäudegeneration Elektro Plus." *Sonne Wind & Wärme*, 2 2013: 28-29.

Manohar R. Kulkarni, Feng Hong. *Energyoptimal control of a residential space-conditioning system.* Carbondale, IL 62901-6603, USA: Mechanical Engineering and Energy Processes Department, Southern Illinois University, 2003.

Navid Haji Maghsoodi, Mohammad Haghnegahdar, Amir Hossein Jahangir, Esmail Sanaei. *Performance Evaluation of Energy Management System in Smart Home using Wireless Sensor Network.* Tehran, Iran. 2012.

Nghiem, Truong. *Modeling and Advanced Control of HVAC Systems.* Truong Nghiem. 2011.

Perez, Richard. "SUNY CNSE." *Suny Collage of Nanoscale Science and Engineering.* 2009. http://www.sunycnse.com/download/Perez.pdf (accessed 11 17, 2013).

Peter Radecki, Brandon Hencey. *Online Building Thermal Parameter Estimation via Unscented.* Fairmont Queen Elizabeth, Montréal, Canada. 2012.

Richard Sickinger, Peter Holzer. *Thermal Comfort.* DI Ralf Roggenbauer, Vienna. 2012.

Simone Dalola, Samir Cerimovic, Franz Kohl, Roman Beigelbeck, Johannes Schalko,. "MEMS Thermal Flow Sensor With Smart." (IEEE SENSORS JOURNAL) 12, no. 12 (2012).

Siti Khatijah Abu Bakar, Abdul Halid Abdullah. "Simulation of Thermal Performance in an Office." Business, Engineering & Industrial Applications Colloquium (BEIAC): IEEE, 2012.

Smart Home. *SmartHome.* 2013. www.smarthome.com (accessed October 31., 2013).

Sultan, Sana. "IMPLEMENTATION OF HVAC SYSTEM THROUGH WIRELESS SENSOR." Second International Conference on Communication Software and Networks, 2010.

Tamim Sookoor, Brian Holben, Kamin Whitehouse. *Feasibility of Retrofitting Centralized HVAC Systems for Room-Level Zoning.* Charlottesville, VA: Department of Computer Science, 2013.

The Energy Detective. *The Energy Detective.* Energy, Inc. 2013. www.theenergydetective.com/ (accessed October 31, 2013).

Whitehouse, Tamim Sookoor & Kamin. *RoomZoner: Occupancy-based Room-Level Zoning of a.* Charlottesville: University of Virginia, 2013.

—. "RoomZoner: Occupancy-based Room-Level Zoning of a." ACM/IEEE International Conference on Cyber-Physical Systems, ICCPS, 2013.

Yahia Tachwali, Hazem Refai,John E. Fagan. "Minimizing HVAC Energy Consumption Using a Wireless Sensor Network." 2007. 439.

Zhenyu Yang, Xiaoli Li, Chris P. Bowers, Thorsten Schnier. *An Efficient Evolutionary Approach to Parameter.* IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS, 2012.