E-quarium, a designer's approach to increasing energy efficiency of households by means of a home energy management system (HEMS)

By Robert Stuursma
August 19, 2021

Contents

1 Introduction

In response to the growing need for consumer energy feedback and management, in 2012, the E-quarium was developed during a student project.

Figure 1 The initial version of Equarium as was prototyped during an earlier student project was a simple two dimensional prototype which could already respnd to energy consumption parameters.

E-quarium is a rich visualization which enables an intuitive representation of the entire home energy flow and affords both an ambient and data-centric approach to data visualisation. The goal of the E-quarium is to optimize energy efficiency within the household in a fun and engaging way to benefit both the user, as well as the environment. To provide all household members with rich insight into energy consumption practices, the challenge was to decrease the cognitive load and required background knowledge associated with the interpretation of typical data-centric solutions, while still being able to provide multiple energy consumption parameters in a single display window.

Figure 2 Due to the success of the E-quarium 2D prototype. In cooperation with Delft University of Technology, E-quarium 3D was born to take the concept further.

A unique approach was chosen by incorporating the metaphor of an eco-system. An eco-system lends itself well for the translation of energy consumption/production data since parallels can easily be drawn such as the level of light in the eco-system and the amount of solar energy that is being produced or water consumption and the water level in the ecosytem. An advantage of the eco-system metaphor is that by means of a natural visualization, the user is able to assess the status of multiple energy variables collected by the hardware backend at a single glance, without the need for comprehensive background knowledge or cognitive skills required by the interpretation of a graph.

This graduation thesis will contain the following topics:

1. A detailed description of the original E-quarium design.
2. A description of the research that explains the necessity of the design, substantiates the requirements that were set for

the design and argues and evaluates the choices that were made during the design process.

3. The final design will be placed within recent development in the field of user interfaces and home energy management.

The first chapter contains an in-depth study into the domain of home energy management. This chapter will explore the three key concepts that will lay the foundation for the rest of this thesis namely “HEMS”, “energy efficiency” and “thermal comfort”. This chapter will be followed up on with a detailed description of the E-quarium design. Subsequently there will be three main areas of investigation which are key to the design of E-quarium. Since in the first chapter the conclusion was drawn that a successful HEMS interface should engage, inform users and in addition provide them with control over the “system”. In these chapters titled Engage, Inform and Control, there will be ample attention for setting up a theoretical / conceptual framework. On the one hand this framework will be employed to explain the necessity of the E-quarium design (relating to the second topic) and on the other hand to evaluate how E-quarium relates to existing systems currently available in the market (relating to topic 3), which ties back in to the question on how the final design fits in with recent developments. It should be noted that the distinction between features engaging, informing or providing control is not clear cut, some features might informative as well as engaging. In the final chapter, this thesis will be concluded.

2 Home Energy Management

In order to formulate a creative approach to increasing energy efficiency by means of home energy management system (HEMS) interfaces, it is imperative to have a solid understanding of the Home Energy Management domain. This chapter will elaborate on three concepts from the domain being HEMS, Thermal Comfort and Energy Efficiency. The order in which these concepts are addressed is arbitrary. However, it should be noted that within the scope of this research these concepts are tightly coupled.

2.1 Home Energy Management Systems (HEMS)

2.1.1 Introduction

When trying to formulate an innovative and creative approach to Home Energy Management Systems (HEMS), it is essential to start with a proper definition of what a HEMS actually is. A definition helps to clarify the scope of the design research, but also provides a framework for comparison and a relevant guideline for a viable design.

Although the term, HEMS, is often used within scientific literature, a clear and concise definition is hard to find. Perhaps this is due to the fact that most authors assume that the wording, “home energy management system” facilitates an implicit understanding. Based on the literal meaning of the words, a HEMS is simply a system that helps household users manage their energy. Unfortunately, there are (too) many devices that would fit this description and therefore it makes sense to choose a narrower definition. Although scientific literature does not provide such a definition of HEMS, an important characteristic of HEMS is interconnectedness. Not only interconnectedness between elements of the home energy management system itself such as sensors and controllers, but also between the system, other connected devices, users, energy suppliers and the internet etc.

The website sustainable-now.eu has the following definition of HEMS (Randall, 2017):

“a technology that consists of hardware and software which are linked and integrated to monitor energy usage, providing feedback on energy consumption and even enhancing control over appliances and devices that use energy in the home. Simply put, these systems allow households to manage their energy consumption more effectively.”

Although this definition is a good starting point in the effort to learn more about HEMS, it is imperative to address some of its implicit ambiguity. A good example of this ambiguity is found in the wording, “enhancing control”. Having control often requires attention, being involved, inspecting what is going on and adapting accordingly. The control a HEMS offers is often indirect, in the sense that the user controls the HEMS and the HEMS autonomously controls the “appliances and devices”. In other words, HEMS facilitate a degree of delegation. Not many people have the time or the motivation to spend a considerable amount of their time on optimizing energy efficiency. Not only are users either unwilling or unable to spend the necessary time that direct control would require, a lot of users simply lack the knowledge and the skills to make the most of full, direct control over their “appliances and devices”. As a result, users have proven to be willing to part with a degree of direct control to make energy management less time consuming, less complex and more efficient.

The aforementioned definition also implies that the usage context of HEMS is within the household (as the word Home in HEMS suggests), while this is not necessarily incorrect, it should be noted that HEMS are often mentioned within the context of so-called smart grids. Load balancing within the electricity grid used to be a relatively simple task, however with the addition of renewable energy sources to the grid and the popularity of electric vehicles, load balancing has become much more complex. The smart electricity grid includes sensors to collect data which is consumed by grid operators to prevent outages and tackle issues (from a distance) when they arise. In addition, the smart grid has the goal to increase energy efficiency on the network level (between households). While the topic of smart grids is, without a doubt, fascinating, it will likely be some time before the promise of smart grids starts directly impacting consumers. With that said, the grid is becoming smarter as we speak, mostly due to the fact of so-called smart meters that constantly transmit usage data to energy suppliers. In fact most households in the Netherlands already have a smart meter (Baas, n.d.). Smart metering along with other sensor data allows energy providers to make (business) decisions on up-to-date factual data with a much higher resolution than previously thought possible. However truly smart features such as demand response, (e.g. the washing machine starting when a neighbor's solar panels are producing energy) and peak shaving (trying to limit energy consumption during peak times), are still some time away. The focus in this paper will therefore be on intra-household efficiency (and not on inter-household / network efficiency). The mechanisms described in this paper to engage, inform and offer control are, however, if not more so, just as relevant within the context of smart grids, since the user would still play an important role.

In a further attempt to clarify the definition of HEMS, in the upcoming paragraph the focus will be on products that have (some of) the functionality that is typically attributed to HEMS. Looking into what products should be considered HEMS and what products should not be considered HEMS, facilitates a better intuitive understanding of the scope of this research. While HEMS can be chosen to mean a complex network of hard- and software, in this research the focus will be on the user interface.

2.1.2 HEMS examples

2.1.2.1 Thermostats

Perhaps most commercially available HEMS fall into the category of thermostats and for good reason. When looking at the energy consumption pattern of a typical household, it quickly becomes apparent that most energy, at least in Dutch households is used, for indoor climate control. Let's perform a simple calculation to show to gain a better understanding of the energy consumed by the typical Dutch household in the form of natural gas and electricity:

Calculation

1 m^3 of gas produces 35,17 MJ of energy upon combustion

1 kWh is equal to 3,6 MJ of energy

So:

1 m^3 of gas produces 9.77 times the amount of energy of a kWh.

About 75% of gas consumed is used for heating purposes.

With the average household consumption being 3500 kWh electricity (for the purpose of running electrical appliances and lighting) and 1500 m^3 (heating, water heating and cooking purposes)

This means 1125 m³ is used for heating purposes, which is about 61% of total energy consumption for an average house hold.

While in the Netherlands indoor climate control is often associated with heating, one might assume that this is not necessarily the case the world over. In countries with warmer climates cooling might account for a significant part of the energy consumed. While this might be the case, it should be noted that climate control in colder climates is significantly more energy demanding than it is in warmer climates as was found in a study where the energy consumption of a “cold” metropolitan area was compared to that of a “warm” metropolitan area (Sivak, 2013). Within the EU at least, the data speaks for itself. Most residential energy is consumed for space heating and only a very small percentage (0,4%) of energy is consumed for cooling purposes (Energy consumption in households, 2021).

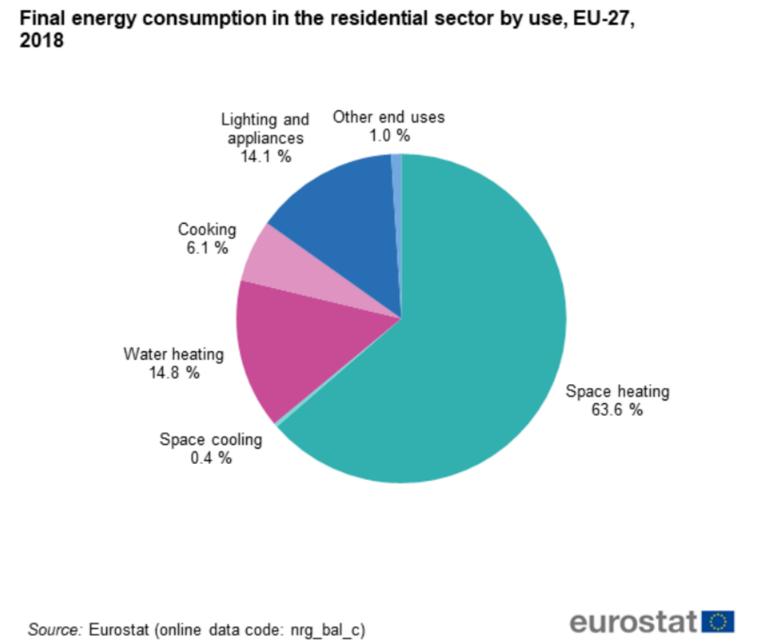


Figure 3 Pie chart showing to what ends energy is consumed by households within the EU

Whether looking at heating or cooling, it becomes apparent that the efficiency of indoor climate control, is one of the most interesting candidates for improving overall residential energy efficiency. In fact, only 14.1% of energy is consumed by lighting and appliances. That’s why in this paragraph the focus will be on the interface between the heating (or cooling) source and the user, namely the thermostat. Thermostats allow users to exercise control over the indoor temperature. While there certainly have been many innovations to the technical aspects of thermostats, this is beyond the scope of this paragraph. The rest of this paragraph instead will deal with the interaction between user and thermostat and how this interaction has evolved over time. Beforehand it is safe to say that especially in terms of user interaction, thermostats have been traditionally known to fall short, as will be elaborated on in the next paragraphs.

2.1.2.1.1 Manual thermostat

The manual thermostat is the thermostat in its most basic and primitive form (see figure 4). A manual thermostat does not adhere to the definition of a HEMS, as follows from the fact that it offers users only a very basic level of control, without giving much, if any, direct insight into energy consumption or many innovative ways to automate indoor climate control besides keeping the temperature at a certain level. While the manual thermostat is connected to the boiler, it does not connect to any other appliances within the household or the internet for that matter.

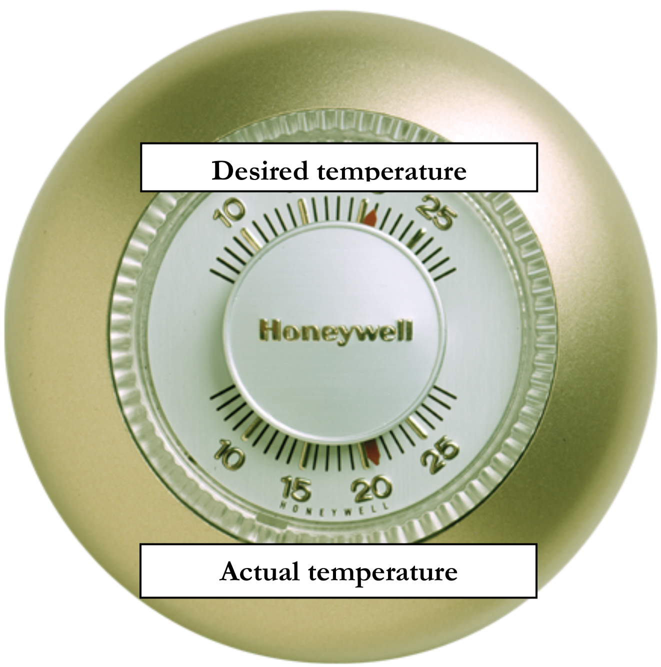


Figure 5 Twisting the outer ring of the thermostat increases or decreases the desired temperature.

While figure 4 shows an analog thermostat, there are also more modern digital manual thermostats (see figure 5). As far as the interaction scheme goes, however there is not much difference apart from the fact that the analogue dial has been replaced by a digital display and often can show the user when the boiler is heating up (depicted by the flame on the left hand side of the display in figure 5).

Figure 4 The digital manual thermostat works almost the same as its manual sibling.

One of the main problems of manual thermostats, whether analog or digital, in relation to energy efficiency is that it takes users to have significant discipline to adjust the set temperature in accordance to their daily lives to achieve optimal efficiency. In theory a user could have his hand on the dial all the time to constantly optimize for comfort and/or cost efficiency. In practice this is not how having a manual thermostat plays out. It is all too easy to forget turning down the heat before leaving the house or going to sleep. This need for active user involvement and the reality of many users not being involved enough, severely hurts the efficiency for these types of devices. A user might have all the knowledge needed about his own context to efficiently control heating, there is still the matter of a user lacking the focus and discipline necessary to adjust thermostat settings accordingly. What also plays a role is that some users do not have a proper understanding of how the heating system actually works. By simply googling the words “higher thermostat faster heating” a variety of articles can be found which explain to users that heating will not go any faster by choosing a higher set temperature. These articles have no doubt been inspired by the experience that user knowledge can be found lacking.

An important note to make is that the trigger to adjust the thermostat comes naturally when a feeling of discomfort is experienced, it takes discipline and conscious effort to turn down the thermostat when there this discomfort cue is not felt.

Design Intervention

Digital thermostats often make it possible to change the temperature setting with a resolution of 0.5 degrees. From an interaction perspective it would be interesting to research the relationship between thermostat resolution and energy efficiency. What effect would it have, if it were possible to set and measure the temperature with a resolution of 0.1 degrees. It could be that such an intervention might lead to energy savings, since a user that would normally set the temperature to 20.5 degrees Celsius, might opt to set the temperature to 20.4 degrees Celsius instead. However, it just as well might be that an intervention such as this might actually increase energy usage or on average or make no real difference for a significantly large user group. Interestingly enough there appears to be very little research on this subject.

Either way a control resolution of 0.5 degrees seems to be generally accepted in devices which are currently on the market. An explanation might be found in the fact that digital room thermostats, although much more accurate than their analog counterparts, lack the accuracy to measure temperature in a resolution higher than 0.5 degrees. In the documentation of the Honeywell DT90E it is stated that this thermostat has an accuracy of +/- 0.5 degrees. The variance of 0.5 degrees between the actual temperature and the temperature that was measured appears to be quite common in room thermostats. This appears to be a reasonable explanation for not displaying temperature in increments smaller than 0.5 degrees, since readings with steps of 0.1 degrees might lead the user to think that the thermostat has more accurate readings, than it actually has. In addition, the readings on the display might fluctuate from one value to the next as a result of random inaccuracies with a variance of 1 degree (-0.5 - +0.5). Inaccuracies in the measurements do, however, not explain why users would not be able to set the desired temperature with a higher resolution. Sure, the thermostat might not be able to accurately measure when the temperature would have been met, but this goes just as well for a setting with a resolution of 0.5 degrees. Setting the temperature to 20.5 degrees Celsius would in practice mean that the thermostat would keep the temperature of the room within the range of 20.0 and 21.0, while setting the temperature to 20.4 would mean it would have to keep the temperature between 19.9 and 20.9, which would lead to some energy savings, regardless of the inaccuracy of the device.

The point could be made that from an interaction design perspective it might be confusing to have a control resolution higher than the actual sensor resolution, however this inconsistency / confusion could easily be solved by a relatively simple intervention. Imagine the following workflow:

The user sets the temperature with a resolution of 0.5 degrees to 20.5 degrees Celsius, then the user chooses a temperature mode saving (set temperature - 0.2 degrees), economy (set temperature - 0.1 degrees), standard (set temperature) or comfort (set temperature + 0.1 degrees). In this way the "temperature mode" would be a modifier for the set temperature, with the benefit that the resolution of the temperature reading is consistent with the set temperature.

Based on the aforementioned design intervention, a case could be made for further research on the resolution of temperature control and its role in energy savings.

2.1.2.1.2 Programmable thermostat

A programmable thermostat, also known as a clock thermostat, has one or more time periods for which the desired temperature can be set e.g. from 00:00 – 18:00 the temperature is set to 16 degrees, while from 18:00 – 00:00 the temperature is set to 20 degrees. The programmable thermostat then makes sure to adjust the indoor temperature in accordance with the program.

Figure 6 The Honeywell Chronoterm T8095. The Chronoterm has been invented by Honeywell in the 1940's and was one of the first programmable thermostats.

The programmable thermostat is already quite a bit "smarter" than its manual counterpart (see the preceding paragraph) and newer versions of the programmable thermostat even contain some basic software. In an absolute sense even these more advanced programmable thermostats still offer only very basic temperature regulation and user interaction strategies, without any feedback on energy consumption. These programmable thermostats can also not be considered to be connected. In that sense programmable thermostats still would not fall under the category of HEMS.

One might conclude that programmable thermostats are an improvement in terms of energy efficiency in comparison to manual thermostats, but this is not necessarily the case as follows from the literature. Peffer et ali. (Therese Peffer, 2012) found that owners of programmable thermostats for the most part either do not use the programming features or they have manually overridden the configured program. In addition, there is the risk of users programming the thermostat once and then lose sight. In the meantime, the user context changes, while the user fails to update the program of the thermostat accordingly. In other words, the theoretical efficiency benefits of programmable thermostats remain theoretical.

The aforementioned problems are likely to be caused (in part) by the fact that programmable thermostats, especially digital programmable thermostats, offer notoriously complex user interfaces. The interfaces of programmable thermostats are rarely, if ever, self-explanatory. This hinders users in reaching energy efficiency goals. Disciplined users might go through the effort of consulting a manual to optimize the programming of the thermostat, while less motivated users are left procrastinating or not paying mind at all.

But even if at one point the programmable thermostat might have been adequately configured, there is the matter of manuals getting lost and attention fading, increasing the chance that the thermostat program will not be in sync with the current requirements of the household. People's lives change all the time, and the thermostat is often not properly reprogrammed to fit new needs. Let's say someone starts working (outside of the home) 5 days instead of 4 days a week. If no reprogramming takes place then the home is heated that day just like it was before, only now there is no one at home to enjoy a comfortable air temperature and energy efficiency deteriorates as a consequence. Users are well equipped to notice when the thermostat is not functioning as desired, when the indoor climate does not meet user needs. However, energy wastage when a user is not in the (part of the) house while it is still heated, is likely to go unnoticed as the user is not physically present to sense the undesired thermostat behavior. As a response to undesired thermostat behavior and the complexity of properly reprogramming the thermostat, the user might opt to manually override the thermostat, leading to the programmable thermostat in effect becoming a manual thermostat.

To put it more specifically, a program is based on the perception of reality. Perception changes and so does reality itself. If programs fail to adapt to these changes or more specifically users do not adapt the programs to meet the changes than programs will become increasingly less efficient. So while programmable thermostats are sold with the promise of saving energy, in practice they often fail to live up to their full potential due to the fact that users do not use the devices as intended by the manufacturer (Todd Malinick, 2012).

Besides the lack of user friendliness of programmable thermostats, there is another very important factor in the efficacy of these devices and that is the household context. The assumption that setting up an indoor heating program leads to energy savings is based on the idea that people lead “regular” lives and houses are unoccupied at least for some part during the day. There are many households where there is always someone at home, in which case elaborate programs offer little value in terms of increased energy efficiency.

2.1.2.1.3 Smart thermostats

The lacking user experience of programmable thermostats paved the way for so called smart thermostats. And indeed it has been shown that not only did more users program their smart thermostat, the accuracy of the program (the ration between the heating of the building and occupancy) was also much better than it was for traditional programmable thermostats (Helen Stopps, 2021). The question is what makes these thermostats smart? One might think that this is an easy question to answer, the truth is however, that manufacturers are very quick to call devices smart. Looking at the smart thermostats available in the market, these devices share one common trait and that is internet connectivity.

The question then arises how and why internet connectivity makes a device smart, well internet connectivity allows for access to data sources (e.g. weather data) that would not have been available to traditional thermostats. Traditional thermostats have some data on the indoor climate, but know very little outside of this context and even then, available information is often limited to the current temperature and the desired temperature. Internet connectivity also makes it possible to have additional control sources (e.g. an app on a smart phone), so a user no longer has to physically interact with the thermostat unit on the wall. This opens a world of possibilities of which a few will be discussed later in this chapter, as these additional control sources can employ algorithms and artificial intelligence to autonomously control the thermostat unit.

Another feature that sets smart thermostats apart from traditional thermostats is the better separation between hardware and software. While some earlier thermostats might have had some software running on a hardware unit, once these thermostats left the factory there was no way of updating the software, as such it can be said that from a user perspective software and hardware were very for all intents and purposes one and the same. This is not the case for the software of smart thermostats, that can be updated over the internet with the purpose of adding functionality and fixing bugs.

So in contrast to the earlier thermostats that have been discussed smart thermostats should be considered HEMS. However, it should be noted that these devices differ in their focus on energy efficiency.

A lot of devices claim to reduce the energy consumption of households but fail to provide users with feedback on their actual energy consumption. Thermostats and even most smart thermostats are often focused on providing users with information about the temperature and not so much how user choices surrounding temperature impact energy consumption. With that said temperature does function somewhat as proxy for energy consumption. Users intuitively understand the correlation between indoor temperature settings and energy consumption. How indoor temperature and energy usage correlate in detail is beyond the grasp of all but the most knowledgeable users.

2.1.3 HEMS definition

Let's look at the definition of HEMS that we started with in this chapter:

"a technology that consists of hardware and software which are linked and integrated to monitor energy usage, providing feedback on energy consumption and even enhancing control over appliances and devices that use energy in the home. Simply put, these systems allow households to manage their energy consumption more effectively."

When taking a look at the devices that have been discussed, while at the same time considering the initial objections to this definition, the following definition for HEMS would be a better fit:

A technology that consists of hardware and software which incorporates locally and publicly available data to provide a users with insight in and control over energy efficiency and thermal comfort while at the same time engaging users to passively and actively use the technology to work towards optimization.

2.2 Energy Efficiency

The term efficiency has already been used a number of times throughout this chapter and although an intuitive grasp has worked fine up until now, a more concrete definition is sure to facilitate a better understanding of the problem domain.

Achieving and/or increasing efficiency in any domain means minimizing input and/or maximizing output. There are a number of processes involved with regulating indoor climate control, but within the scope of this research, it would not make sense to focus on the physical process of generating and transporting heat (e.g. operating a central heating system). Since the physical efficiency of indoor climate control is (except for the purchasing decision)to a large degree outside of the user's control and much more a property of the central heating system itself.

A useful definition of efficiency requires terms which are inside the control of the user (at least as far as input goes). From this perspective it makes sense to define efficiency in terms of indoor climate control program, the collections of desired temperatures over a certain period of time (input), versus thermal comfort of the user (output). The concept of indoor climate control program as input, might be somewhat counterintuitive. Visualizing the indoor climate control program as a line graph facilitates a better understanding of the concept. By taking this mathematical approach, the indoor climate control program can even be brought back to a single number by taking the sum of the temperature settings over the course of the week. The benefit of a single number for the input is that it makes it possible to easily compare climate program values between households. With that said, in practice it will be quite hard to bring back the indoor climate program to a single value (that is within the control of the user), due to the fact that a typical house consists of multiple rooms. In most households there will be single wall mounted thermostat, while radiators are operated with a valve (which may or may not include thermostat functionality). For simplicity's sake we will ignore this fact for now.

It should be noted not to confuse energy efficiency with energy saving. Efficiency, as a concept, is different in the sense that increases in efficiency will lead to saving, but, not necessarily all saving leads to increased efficiency. One could imagine reducing the desired temperature on the thermostat which as a result reduces the air temperature which in turn reduces thermal comfort. This type of saving cannot be considered sustainable, since users are likely unwilling to endure thermal discomfort over longer periods of time. To simplify matters further the goal of increasing energy efficiency can be defined as reducing the input of the indoor climate control program, while maintaining the user's feeling of thermal comfort.

2.3 Thermal comfort

In the previous paragraph the term thermal comfort has been introduced. It is now time to look at thermal comfort in more detail and see how well it lends itself for a creative approach towards better energy efficiency.

Thermal comfort is defined as "the condition of mind which expresses satisfaction with the thermal environment". There is a constant exchange of heat going on between the human body and its environment. This exchange is proportional to the difference in temperature between body and environment. When the user loses too much heat to its environment, the user will feel too cold and when the user is unable to release enough heat to the environment, the user will feel too hot. Thermal comfort can therefore be described as the status of neither being too hot or too cold. It should first be noted that thermal comfort is very much dependent on contextual factors and as such there is not a one size fits all approach possible. Even psychological parameters, such as individual expectations (Haiying Wang, 2020) and perceived control (Maohui Luo, 2016) affect thermal comfort. Subsequently it is important to realize that thermal comfort is only in part determined by air temperature (which the thermostat actually tries to regulate). Other factors that play a role in thermal comfort are those factors that in general play a role in body heat gain and/or loss.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers describes the following factors for thermal comfort in the ASHRAE 55 standard:

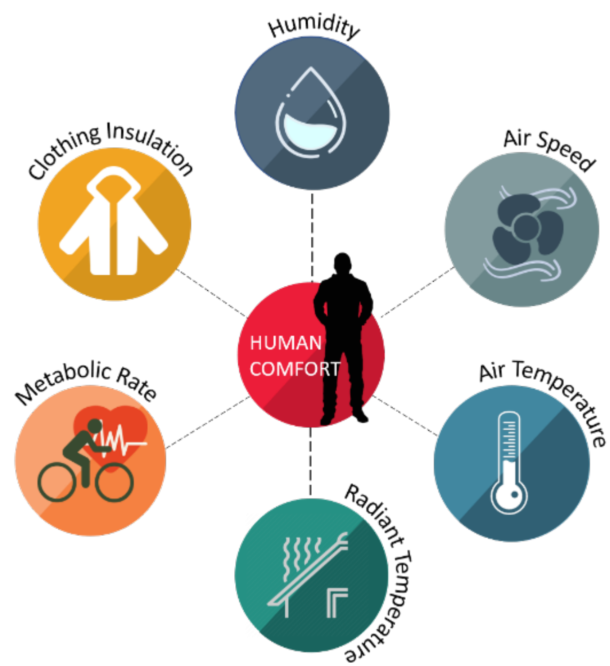


Figure 7: A simple diagram portraying the factors in human comfort

Airspeed

This is basically the movement of air and is also known as the air velocity. The higher the air speed the more heat exchange will take place (M. Fountain, 1993). This can be used to the advantage for indoor climate control. In warmer climates the air temperature could be lowered but a different strategy would be to increase the air speed. It should be noted that there is a relationship between air speed and temperature. If the temperature difference between the air and a surface becomes greater, the air speed also increases hereby creating more heat exchange between surface and the air.

Clothing insulation

It will not come as a surprise that thermal comfort can be influenced by clothing. If you're cold, just wear a sweater, simple as that, and if you're hot just take that sweater off. CLO is the unit that is used to express the thermal insultation that is provided by clothing. The CLO value has been set equal to 1 for the clothing insulation required for an inactive human to maintain thermal comfort when the indoor air temperature is at 21 degrees Celsius. Lower values indicate lower insultation typical for summer clothing, while higher values indicate better thermal insulation typical for winter clothing.

It is interesting to note that typically clothing is viewed as a fashion item more than an item that protects us against the cold or in hot environments allows us to cool down as much as possible. You might be able to find "warm" in the description of a clothing item in a typical web shop. But how one "warm" sweater compares to the next is hard to determine as a customer or if warm is in fact really warm.

Relative Humidity (RH):

According to Wikipedia Humidity is the amount of water vapor which is present in the air. Depending on the temperature, air has a maximum humidity, in other words the maximum amount of water vapor which can be present in the air. Relative humidity is the ratio expressed in a percentage of the actual humidity and the maximum humidity. When humidity is high it will be harder to dissipate heat through perspiration leading to discomfort. A humidity which is too low does not only cause thermal discomfort but also a sensation of dryness (Nobuko Hashiguchi, 2009)

Mean Radiant Temperature (tr):

The uniform surface temperature of an enclosure where an occupant would exchange the same amount of heat as in the actual non-uniform space, calculated from the weighted temperature average of each surface divided by the total area of the space.

Metabolic rate

Calories are burned within an organism to produce energy for a variety of reasons among which to keep body temperature stable or to perform some action, but also internal processes, keeping the organism alive, require energy (Fernando J. Ballesteros, 2018). Metabolic rate is expressed in terms of watts produced per m^2 of body surface area. The human body has only limited efficiency in the sense that much of the energy is dissipated as heat. When a person is at rest his metabolic rate is 1, the higher the metabolic rate the more heat will be generated by the human body.

Figure 8 The more intense the activity, the higher the metabolic rate as can be seen in the above diagram.

3 E-quarium

3.1 Introduction

Recent developments such as smart metering and energy efficient wireless network technology have made it possible to collect data about the energy flows inside households. All this data has given rise to the question how it can be put to use to benefit energy efficiency and thermal comfort. This has resulted in a flourishing new industry that builds interfaces that fit the bill of Home Energy Management Systems (HEMS). HEMS provide the user with insight and control over their personal household energy context, while at the same time trying to deal with the challenge of keeping users engaged.

3.1.1 Data centric approach

With the HEMS available in the market nowadays there are basically two approaches, which are used to inform users. There is the data centric approach where graphs, tables and numbers are incorporated to provide users with insight. Although in theory a lot of data can be conveyed in this manner, in practice a data centric approach requires a user spending time and attention to properly interpret data. In addition, the user needs to have the right level of background knowledge. There are significant problems with the data centric approach. Most people either lack the time, the cognitive skills or the background knowledge to benefit from the information that data centric HEMS are trying to convey. Just think to yourself how many people really know what a kWh actually is?

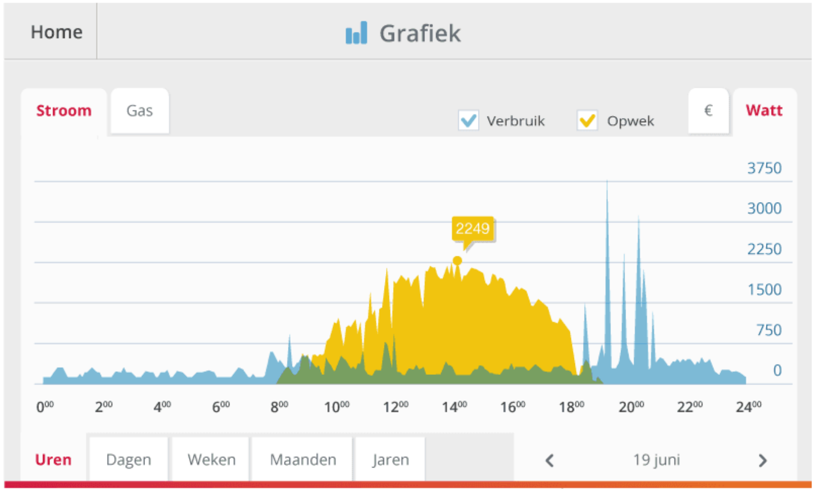


Figure 9 Eneco Toon is a good example of a data centric approach. The user is greeted in the interface by tiles containing numbers and graphs. By clicking the tiles the user is able to deep dive into more detailed graphs.

3.1.2 Ambient approach

Then there is the ambient approach where there is a simple interface that through a light, sound or movement provides insight on energy efficiency. Ambient basically means environment. So ambient feedback means feedback that blends into the environment and as such surrounds the user. Since the ambient approach is much simpler than its data centric counterpart, it requires less time to be interpreted, it requires less background knowledge. However therein also lies the main problem of the ambient approach, the amount of information that can be conveyed is very limited. As such the data centric approach is dominant in the market, with the ambient approach having little to no foothold at least when it comes to HEMS.

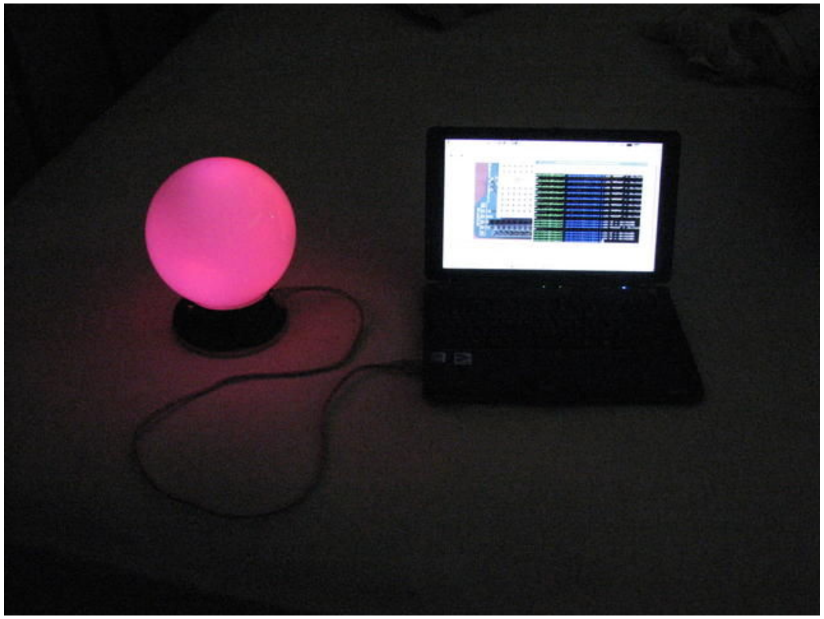


Figure 10 The Energy Orb is an example of an ambient approach. The light of the orb is dependent on the actual cost of energy indicating to users when the best time is for energy consumption in a non-obtrusive way.

In part that might be due of the fact that for those users who are interested in the ambient approach, it can be implemented without too much trouble. With smart lighting systems such as Philips Hue, the color of the light can then be augmented on the basis of energy parameters quite easily through a framework such as IFTTT (https://ifttt.com/).

Figure 11 IFTTT connects multiple API's from popular appliances to allow for devices and sensors to work together by means of programs call recipes.

Although setting up an ambient feedback system as described before, is not particularly difficult, the whole process still involves some complexity and requires a rudimentary understanding of programming and the energy context. Users that would typically benefit the most from the ambient approach are those users that lack the background to properly setup such a system themselves.

While the ambient approach might not be popular in the domain of HEMS there are a number of examples where smart plugs offer the option to react to energy consumption such as the Fibaro wall plug.

Figure 12 The Fibaro wall plug shows energy consumption from the plug is visualised through lighting up the rim of the plug with a color.

3.2 E-quarium design

From a co-design session with a number of households of mostly older couples (which were of above average in terms of education) it became clear that some household members were very much attracted to a data centric approach, while their partners on the other hand felt alienated by these types of data centric interfaces and actually indicated that they would not like such a system hanging in their living room. It turned out that these household members actually were much more attracted to a system that would nicely blend into the living room. Of course, this this conflict of visions can be detrimental to the effectiveness of the interface since a single member of the household can perform actions. Since any and all household members are involved in energy management, a design that would lead to resistance from one of the household members could severely impact the efficacy of the design. Any design that would supposedly contribute to energy efficiency would therefore need to provide an integral approach, involving all members of the household.

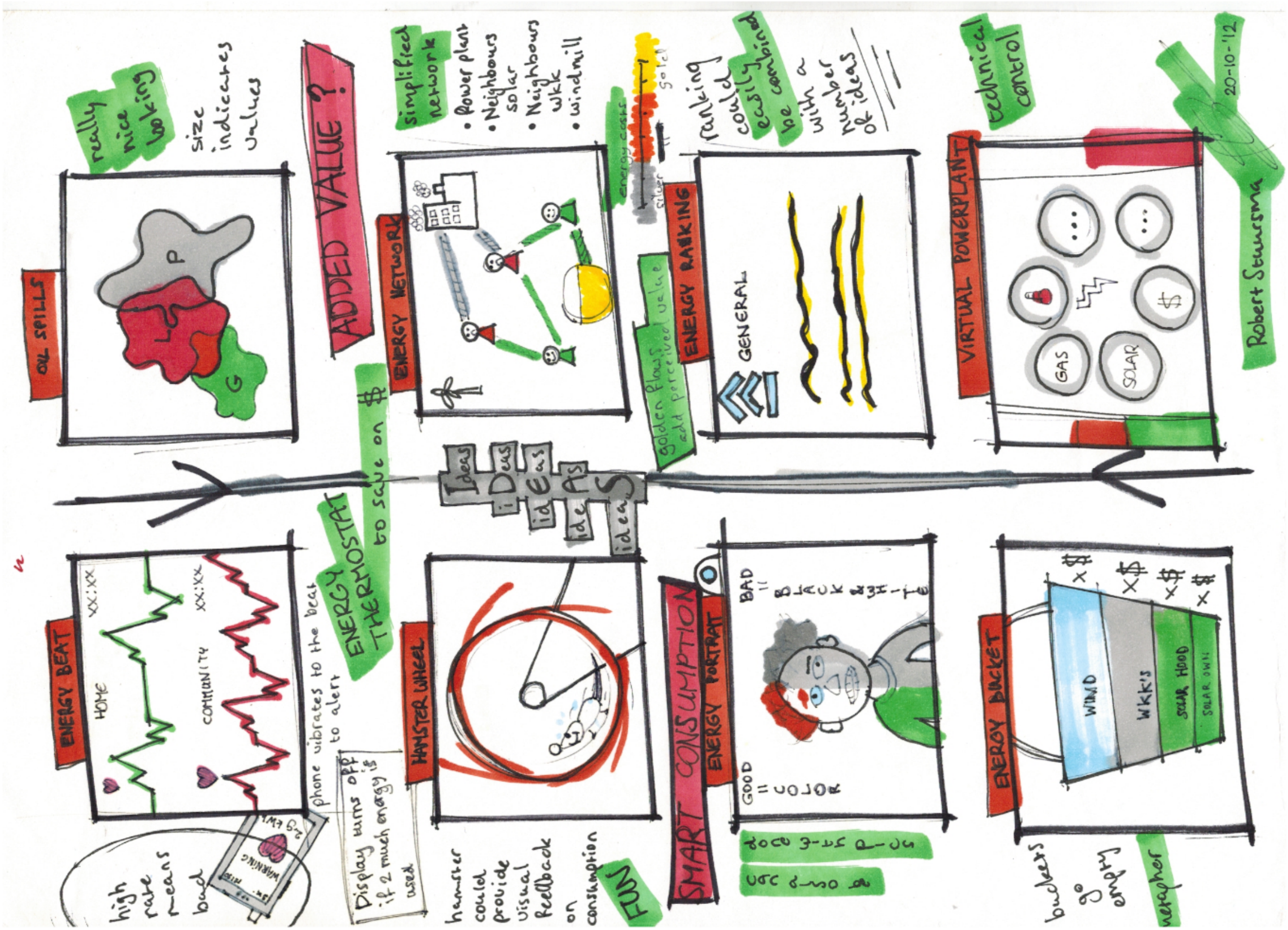


Figure 13 Based on the insights gathered from the co-design session, it was decided that the typical datacentric approach would cause too many impediments for a proper understanding of energy consumption / production in the household context

Figure 14 Quite some metaphors were explored such a hearth where the height of the flames would signify energy consumption.

After a significant amount of brainstorming based on the insights that were collected during the earlier co-design session and the literature research that had been performed at an earlier stage, from which it became clear that many users lost interest for HEMS after a relatively short period. the idea for the E-quarium emerged. The E-quarium had the richness of a data centric approach and the simplicity of an ambient approach.

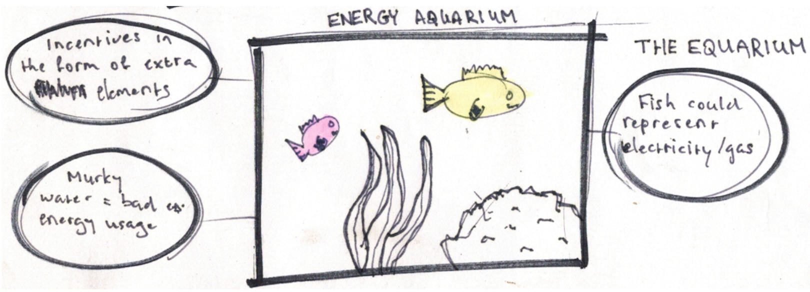


Figure 15 The first sketch of the idea behind E-quarium.

3.2.1 Natural visualization

So, what is E-quarium? E-quarium is a virtual digital ecosystem in the form of an aquarium which can be run on a tablet, phone or wall mounted device. E-quarium responds to the household's energy context. When users are managing the flow of energy inside the household in an efficient manner, the ecosystem flourishes, while inefficiency leads to a deterioration of the aquarium environment. An important insight behind the E-quarium concept was that people from an evolutionary perspective are able to quickly interpret a natural "environment" and in addition detect changes to a natural environment intuitively.

To facilitate data richness the ecosystem does not change as a whole, but different environment variables (e.g. plant growth, water quality etc.) can change independently.

Figure 16 The first prototype of E-quarium, E-quarium 2D, where the main purpose was to engage the user through an appealing anthropomorphic pet energy coach.

These environment variables can then be linked to the available energy data which is provided either by a sensor network or the internet. It should be noted that the collection of the data is not a topic that will be addressed in this thesis. To give some concrete examples of how this would work in practice consider the following example. Plants could slowly disappear when the thermostat would be used inefficiently or the water level could go down when water consumption goes up as a result of long showers.

3.2.2 Energy coach

To make the interface even more engaging and informative a fish is part of the E-quarium that serves the imperative role of personal energy coach. The fish is ready to support the user in many ways. For example, the fish can provide the user with tips and feedback through a dialog mechanism. In addition, the fish can become the face for home automation in the sense that it's not a faceless computer system that is taking care of automation but an actual actor in the form of a fish to which the user can relate. Putting a face to a system that normally doesn't have one, personalizes the experience. The essence of the design is to provide the user with a sense of control by being able to delegate actions to an entity to which he feels some type of bond.

Figure 17 After the success of the initial 2D prototype Paladin Studios, a game development studio, was hired to take E-quarium to the next level.

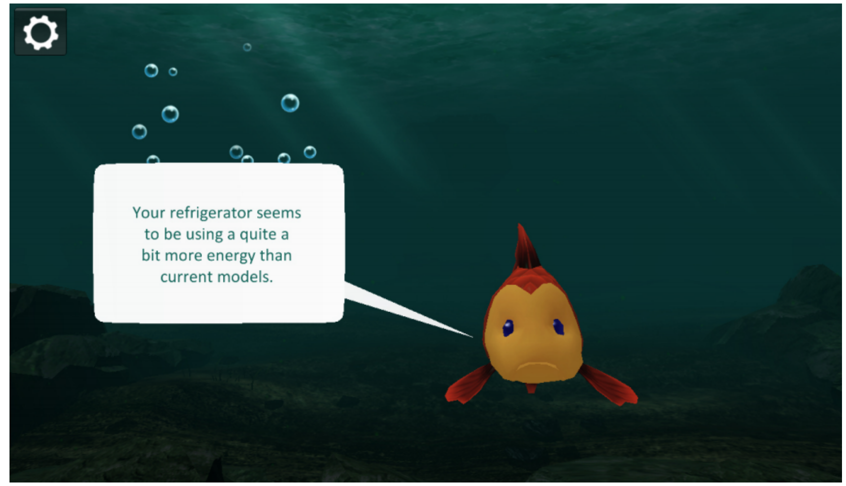


Figure 18 The fish is sad and the environment looks very gloomy indicating to the user that action is required.

The way the fish is able to emote in combination with the fact that it is reliant on the eco-system for his "survival" which in turn is directly dependent on the performance of the user on energy efficiency goals, works to create an emotional bond between the user and the virtual agent, not unlike the bond that has been found between children and their virtual pets during the Tamagotchi craze. This social component (relationship between user and fish) can then be leveraged to further motivate the user towards a more energy efficiency within the household.

Figure 19 https://www.trustedreviews.com/news/tamagotchis-return-with-google-chrome-extension-3287756

3.2.3 Data centric

E-quarium has been designed to provide information on energy efficiency in a quick and simple manner. At a single glance a considerable amount of data can be interpreted by the user as he simply needs to evaluate the state of the ecosystem and the expressions of the fish. Although one of the reasons of being for E-quarium is in the fact that lots of users have difficulties interpreting datacentric views, is was decided that E-quarium should also feature data centric views. What makes the data centric views inside E-quarium different from traditional data centric views is that E-quarium tries to provide context inside these views, by adding text labels to a graph and explaining what the user is looking at. This is part of the scheme to educate users, to help them gain a better understanding one step at a time.

Figure 20 A typical graph in E-quarium will not show numbers, but in stead show how the user compares to some benchmark that has been established for him.

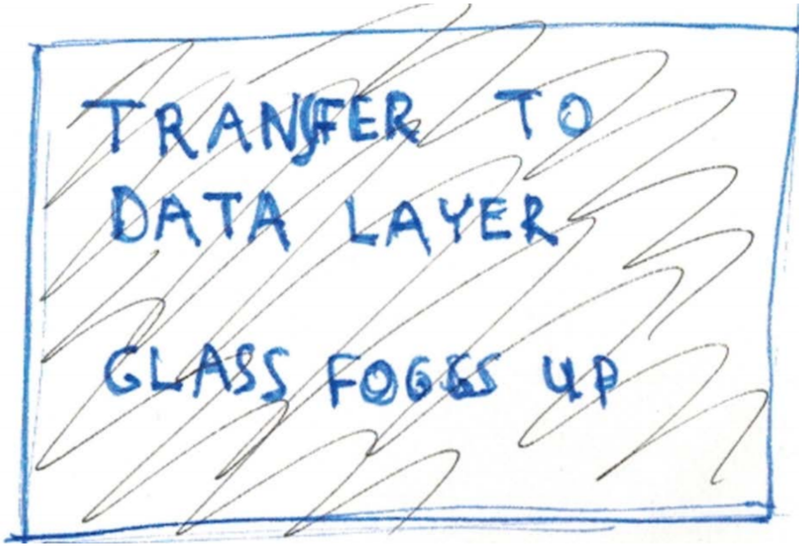


Figure 21 The glass fogging up creates a canvas for the data centric views.

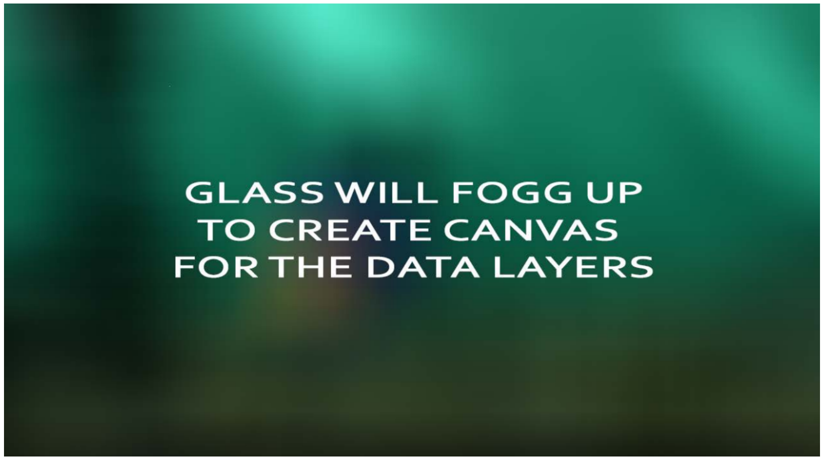


Figure 22 A look at the final implementation of the glass fogging up.

3.2.4 Communication

For the user to be able to communicate with the fish, an interaction scheme needed to be implemented. While at some point voice control would be the logical option, this was too far-fetched for a minimum viable product. At the same time the user would still need to feel that he was actually communicating with the fish. That's why the choice was made to create a circular menu with the fish in the center in essence "listening" to the user. By tapping the screen (which in itself is a metaphor for the aquarium glass), the fish swims towards the user and the menu appears around the fish. There, the user can choose between various options to get more information or exercise control over his energy context.

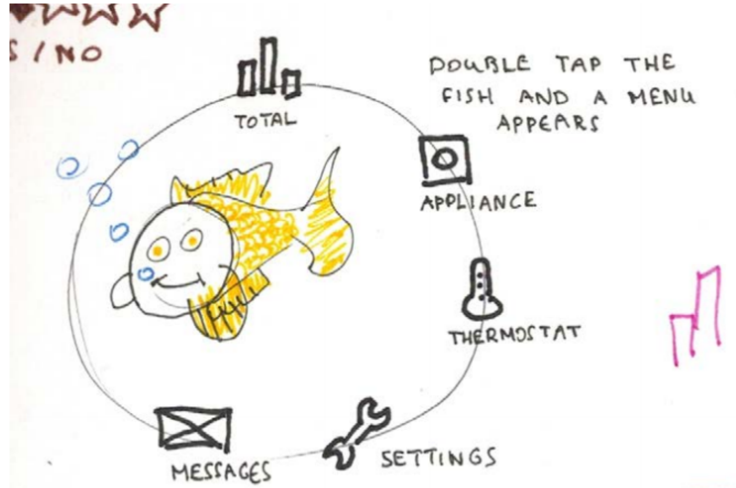


Figure 23 The first sketch detailing the communication / menu scheme.

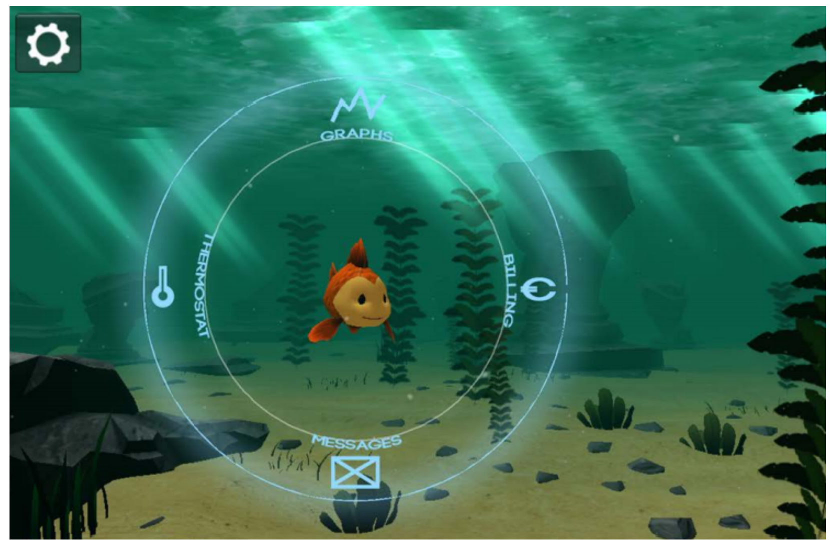


Figure 24 What the actual implementation of the communication / menu scheme looked like.

This tapping the aquarium glass interaction also plays a role when the fish wants to share an alert (e.g. a tip, feedback etc.). The fish swims up to the glass, waves to the user and a small thinking bubble is shown to indicate that the fish is looking to communicate with the user. When the user, then, taps the glass the fish will share its message with the user.

Figure 25 The first sketch of the alert feature.

Figure 26 The alert feature in action.

4 Engage

While we might be headed towards a future where people easily hand over control to ubiquitous computers, there still is a long way to go. There are examples a plenty of people willing to hand over some control to some devices. However, this often leads to problems when a device behaves in a way which is counterintuitive to the user. Then there is the fact that energy efficiency requires attention, focus and discipline for this reason specifically it is important to engage people. If a HEMS interface design fails to engage it cannot achieve the goal of increasing energy efficiency. In this chapter the focus will be on the topic of getting and keeping the user engaged.

4.1 Motivation

In getting people to change their behavior, they have to be motivated to do so or there is little chance of success other than a miracle happening. Motivation is the impulse, the drive and/or the inspiration that gets people to take some form of action. It is important to realize that motivation is not just some binary term in the sense that someone either is motivated or not. Ryan and Deci (Richard M. Ryan, 2000) state that motivation varies in level (how motivated is someone?) and orientation (what type of motivation does someone have?). Common knowledge dictates that motivation is heavily dependent on the combination of individual, activity (or action) and context. While some people (individual) love to go out running (activity), they might find it an absolute nightmare when it's raining (context).

In researching the subject of motivation types, one quickly finds the most basic subdivision to be, between intrinsic and extrinsic motivation.

Intrinsic motivation is often described as the motivation for activities that are inherently rewarding. In other words, situations in which the road and not only the destination is fun, interesting, exciting, engaging etc. While extrinsic motivation is described as the impulse to do something simply because it leads to an outcome that is considered to be rewarding, while the activity in itself might not be motivating at all. Intrinsic motivation has been considered to be of more use in terms of meaningful change in the behavior of people in comparison to extrinsic motivation which is of lesser value in terms of inspiring change. In order to gain a more thorough understanding of the subject of motivation it will pay off to look into why extrinsic motivation is less potent than its extrinsic counterpart. Before diving deeper into this subject matter, one should learn that in most if not all cases motivation is not just intrinsic or extrinsic, it is a combination of both. In the next paragraph it is shown that there is an interplay between intrinsic an extrinsic motivation.

4.1.1 Intrinsic versus extrinsic motivation

In the field of psychology, extrinsic motivation is seen as a force that leads to desired effects in the short term, while having very little influence on the long term (persistence). Kohn (Kohn, 1993) has evaluated numerous programs for changing people's behavior for the better (e.g. stop smoking, lose weight etc.). He found that although in the short-term participants that were rewarded (a form of extrinsic motivation) were more likely to have better results, but the group that did not receive any reward (extrinsic motivation) had better results in the long term.

Extrinsic motivation has also been proven to decrease intrinsic motivation. Before going into this matter further it is helpful to know how intrinsic motivation is measured. Determining intrinsic motivation is often done by creating a scenario in which a participant is asked to perform an activity for some amount of time. After that time is up, researchers will then measure how much longer participants will continue with the given activity. The longer the participant continues with the activity the higher the intrinsic motivation is said to be. In a research setting where one group was rewarded for performing an activity and another group did not receive any reward (nor were they promised any reward), the unrewarded group would on average continue longer with the given activity than the rewarded group. Condry and Chambers (Condry, 1978) attribute this to the fact that rewards take the focus away from the activity (process) and places it instead on getting the reward, overall hindering engagement. Intrinsic motivation focuses attention on the journey and not on the destination. The more important the destination in relation to the journey becomes, the more intrinsic motivation will be diminished as a consequence. As intrinsic motivation dwindles so will re-engagement (persistence). A reward can motivate someone to do something once. But that's not to say that the exact same reward will keep motivating someone to do that something. This, in fact, is extremely unlikely.

In general, it can be said that intrinsic motivation is fragile to the influence of all matters that hinder the autonomy of the individual (Liang Meng, 2015). Extrinsic motivation is one such element, but there are other factors as well such as competition. Fostering intrinsic motivation therefore requires facilitating control. Which is not the same as saying that where there is control, there is intrinsic motivation. Autonomy is a requirement for intrinsic motivation.

Before going into practical factors of the motivation of people to play a more active role in energy management, it is important to note that most people will lack a strong intrinsic motivation to manage energy usage. One can assume a number of reasons such as the lack of confidence in being able to improve energy management to a significant degree, the lack of impact of your contribution to overall energy efficiency or a lacking sense of urgency.

4.1.2 Extrinsic motivation: Energy costs

While some people will sincerely want to improve energy efficiency in order to contribute to a more sustainable future, there is likely to be a more significant group for whom cost saving will be the main driver towards the improvement of energy efficiency within the household. There are a number of factors at play that impact the effectiveness of price as a motivational factor though. In the Netherlands a direct connection between behavior and cost is missing to a large degree, in the paragraphs below this will be explained further.

4.1.2.1 Delayed reward and penalty

What is most interesting to note about the billing model in the Netherlands is that the amount of energy you are actually billed for is always based on your usage in the previous year and not on your current usage or your usage in the past month for that matter. If you have used 2450 kWh in 2018 this is the amount of energy you are billed for. Even if you have managed to cut back on usage greatly from January 2019 onward, you will not see this on your energy bill until January 2020. This means a very significant delay in terms of the reward for good energy behavior. The exact same argument could be made for the penalty in the case of bad energy behavior, which also comes with the same amount of delay.

Woolley and Fishbach (Wooley, 2018) describe the temporal proximity of a goal to a reward. In other words, how close in time the reward (e.g. saving on your energy bill) and the activity (e.g. replacing your refrigerator for a more efficient model) are related. They found that the closer in time the reward and activity are, the more likely it is that intrinsic motivation for the activity will increase. It is theorized that this effect can be chalked up to the fact that a closer relationship between activity and reward arises.

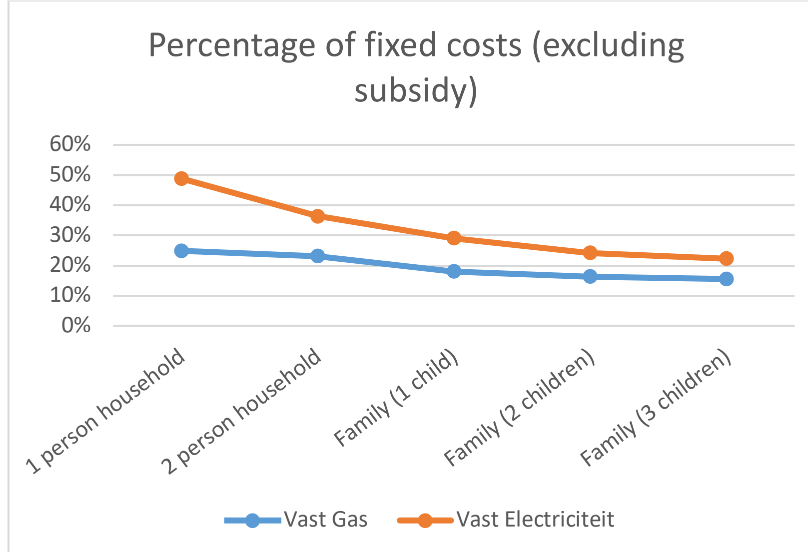
Then there is the theory of delay discounting, which is best described by an example. Let's say someone would get 20 euro in 2 weeks. People generally prefer an immediate reward over a reward in the future and are therefore willing to settle for a smaller reward if it is received now. This effect of discounting has been shown to vary among people with some people being able to withstand temptation and delay gratification, while others choose the immediate reward even if this comes at a significant cost.

Temporal proximity and delay discounting are just two factors at play when considering how the billing structure in The Netherlands hurts motivation to increase energy efficiency. Then there still is the question of whether the reward (savings) or the punishment is significant enough to form extrinsic motivation for behavioral change.

4.1.2.2 Fixed costs vs. variable costs

The fact that the energy bill consists of fixed costs and variable costs (based on actual usage) is another inhibiting factor for motivating behavioral change.

Let's say someone in a single person household manages to cut down on energy usage by 10% from 1500 kWh and 1000 m^3 to 1350 kWh and 900 m^3. The annual energy bill would go from EUR 1.359,- to EUR 1.249,- which is not a saving of 10% but of 8%. No matter how hard consumers increase energy efficiency their fixed costs will never go down.



4.2 Trust

In the pursuit of creating a HEMS that truly makes a difference, trust between man and machine is essential. If trust between user and HEMS is missing, a situation might arise where theoretical improvements in terms of efficiency are not attained due to the user being involved in processes which are better left to be under the autonomous control of the HEMS.

Before exploring the subject of trust between man and machine further, it is likely to pay off to delve a bit deeper into what trust actually is. Based on many definitions found in literature it can be concluded that trust is always in someone or something and is always a positive expectation of that something or someone. In that sense it could be considered the antonym of fear, which can be defined as a negative expectation. But this is not quite the case, or at least not in the way that one would expect. The main difference between trust and fear is their relation to behavior as follows from the definition posed by Scanzoni (Scanzoni, 1979):

“Actor's willingness to arrange and repose his or her activities on [an] Other because of confidence that [the] Other will provide expected gratification”

Trust per definition implicitly includes the willingness to act in accordance to the positive expectation, while the definition of fear does not necessarily include the willingness to act on the negative expectation. On the contrary, in everyday language fear is often used in spite of action such as I’m afraid my current endeavor might fail (spoken while still pursuing the endeavor). Trust is the certainty that positive outcomes will follow, while fear is the uncertainty that negative outcomes will follow.

4.3 Approaching comfort vs. avoiding discomfort

From an engagement perspective it’s interesting to answer what carries more weight moving towards comfort or moving away from discomfort. Within the field of psychology these concepts are known as approach and avoidance (Tyson V. Barker, 2019). Within the context of increasing efficiency, it is important to determine an interaction scheme that takes approach vs. avoidance into account. The hypothesis is that the feeling of discomfort weighs stronger than the feeling of comfort. For primitive concepts such as comfort it can be stated that comfort can be seen as the absence of discomfort. Whether this is true or not, the point could be made that most of the interaction between user and thermostat is inspired by a feeling of discomfort. A user feels either too cold or warm and takes action to improve thermal comfort accordingly. When the user is within the range of thermal comfort, it is likely that the user is no longer triggered to be concerned with thermal comfort since his needs have been met. After eating you’re very likely to be unconcerned about food.

4.4 How do commercially available HEMS engage?

Google Nest uses leaves to stimulate customers to select a slightly lower temperature (or higher when it comes to air conditioning) than they normally would select. This seems like an interesting approach. Nest focusses not on the actual energy consumption, but on the temperature setting. When the user chooses a temperature that departs from the automated program in a way that is beneficial to energy consumption, the user’s account is awarded a leave. At the same time the automated program is learning from the settings that the user makes, so over time it gets harder to earn leaves. This strategy appears flawed in nature. The leaves will most likely provide little extrinsic motivation, as the leaves have little value more than novelty value, especially when compared to the discomfort which will be a much stronger motivator. So, saving actually still comes down to intrinsic motivation. However over time the user that is intrinsically motivated might experience the leaves as being demotivating. As the leaves are relative to the user’s own usage, meaning that a user that is already performing quite well will not earn any leaves. That can have a demotivating effect. While it is a known fact that extrinsic motivation can lower intrinsic motivation, it is interesting to see what happens if the extrinsically motivating factor also diminishes over time. With that said in the ideal circumstance you would be rewarded for performing at the same efficient level over longer periods of time, so instead of diminishing returns, you would like to see increasing returns, yet this is not how Google Nest works.

Figure 27 The Google Nest thermostat

Figure 28 The accompanying app of Google Nest provides users with an overview of the leaves that they have earned

Figure 29 A look at the Tado app which seems to have a bit more focus on saving money for its users as the piggy bank in the interface implies.

Tado focuses mostly on the cost saving aspect of HEMS. Since the cost saving is solely related to the automation features of the systems such as geofencing, open window detection and weather adaption, the question is what type of engagement this will foster with the user. Since the user himself has little to no influence on this saving, it would seem that this feature is mostly geared towards influencing the purchasing decision of the customer towards buying a Tado smart thermostat. How often would the user consult a feature which gives him data on which he has no influence and seems to have the goal of convincing the user how well the system is performing. In addition, the question is what the saving percentage actually means. Apparently a savings percentage is calculated by taking the amount of energy that would have been used, if the automated features would not have been there. This comparison does not seem fair, since these features themselves influence the way the user interacts with the system. Where a user might have at first turned down the thermostat, the user can now just leave the home and the geofencing automatically turns down the thermostat. While we could delve deeper into the savings reports that Tado provides, this is likely to provide little more insight than already collected. In short the savings report contains a percentage that is calculated by taking the current situation and comparing it to a hypothetical situation in a somewhat subjective manner. In 4.1.2 it was already shown that saving energy and saving costs is not as simple as it looks.

In summary the HEMS which are available in the market don't seem to focus that much on engaging the user. Most devices seem to automatically assume that because the device is there, it will automatically lead to savings. Although some automated features which HEMS bring to the table do actually have the potential for improving energy efficiency, the general assumption among the marketing of these devices seems to be that insight and improved UX automatically leads to savings. While providing the user with insight is definitely an important factor in improving energy efficiency, it is in no way equal to it. The user needs to be willing to make and accept changes to make meaningful changes. This requires user involvement, in other words the user needs to be engaged over a longer period of time. While the user will likely be engaged in the first months after the purchase of the device, after all the user made a conscious buying decision, that is not to say the interest in the HEMS will slowly dwindle over time.

4.5 How does E-quarium engage?

4.5.1 The Tamagotchi effect

People are social by nature, leveraging this innate human characteristic can lead to truly compelling designs. The Tamagotchi was one of these products that tapped into the caring and social nature of its users.

Figure 30 The original Tamagotchi was first introduced in the market in 1996 and was all the rage among younger children. In some schools it was actually prohibited to bring Tamagotchi's as it would cause too much distraction.

What was truly unique about the Tamagotchi that it managed to capture the user with a very simple and basic interaction scheme and even simpler graphics. The virtual pet would grow from a baby to one of 6 adult types depending on the quality of the care the user provided. Although there were only a limited number of actions that were available to care for their virtual pets, some users got so attached to their pet that they were reduced to tears when it passed away. The Tamagotchi served no real motivational purpose beyond the scope spending time with a virtual pet, but the Tamagotchi did spawn some interesting ideas. One of the first product concepts that managed to harness the underlying motivational power of the Tamagotchi was the Pocket Pikachu (see Figure 31) which was basically a Tamagotchi with a built-in step counter. Pikachu is an electric mouse and is one of the main characters in a popular children's television show. In order to charge Pikachu's electricity children would have to walk or run, in this manner children were stimulated to be active. If the user was inactive this would result in their Pikachu retaliating by becoming angry and no longer recognizing the user. The Pocket Pikachu was mentioned as the most popular exercise tool of its time in the Guinness Book of Records.

Figure 31 Quick to follow the rage of the Tamagotchi was Pokémon Pikachu in 1998. This Pokémon (popular Japanese franchise) themed Tamagotchi clone was no mere me-too product, due to the twist of the included step counter which was a vital part of the experience.

There have also been a number of research projects with the focus of leveraging a virtual pet in order to motivate people to take action. An example from literature is Fish 'n Steps (James Jeng-Weei Lin, 2006) which links physical activity to the wellbeing of a virtual character in the form of a virtual fish. In this study it was shown that a virtual actor can inspire users towards lasting changes to lifestyle.

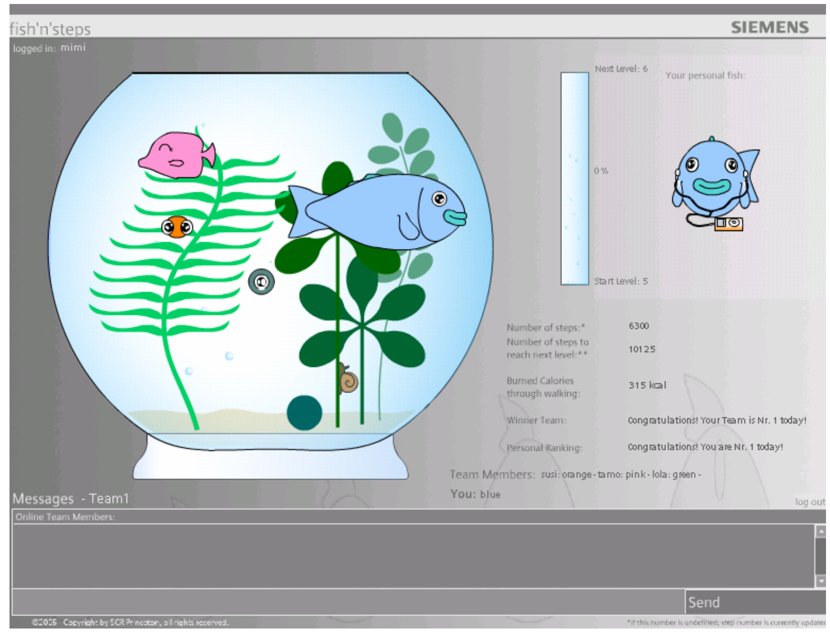


Figure 32 Fish'n'Steps was a computer game created for a research project to see whether gamification could play a role in improving the activity level of its users. The virtual fish bowl even contained the fish of friends to add a competitive and social element to the equation.

More related to the topic at hand was a different research project featuring a Virtual Polar Bear (Dillahunt, 2008) which was intended to motivate users to demonstrate environmentally sustainable behavior. The performance of the user was linked to the amount of ice that the polar bear had to stand on. The results of the study show an improvement in desirable behavior, this effect was even more noticeable when the user became emotionally attached to the virtual pet.

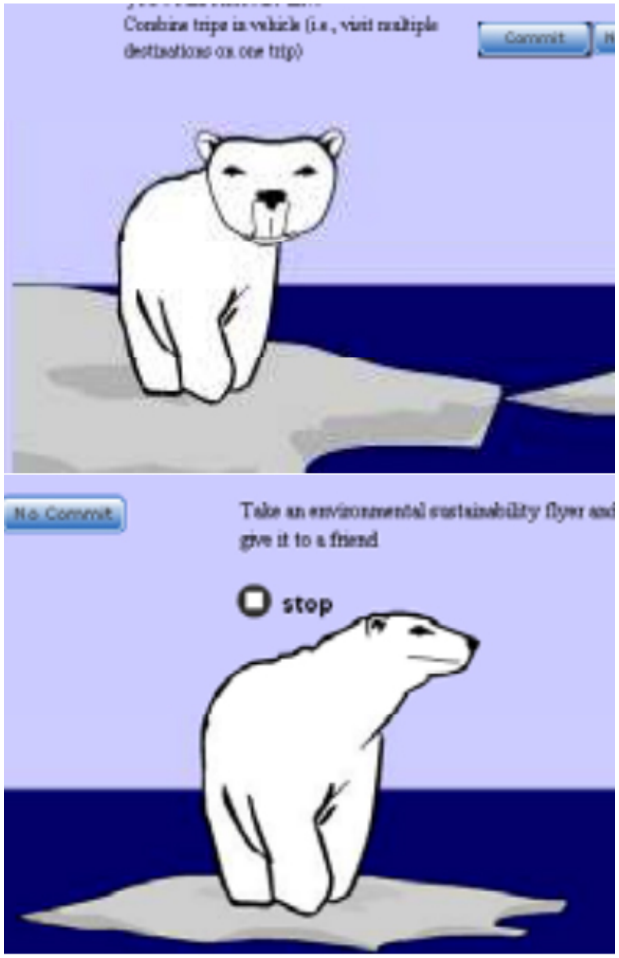


Figure 33 Climate change as a result of massive energy consumption is often associated with melting ice in the Polar regions. A polar bear on a melting ice floe connects well to public perception.

The findings discussed in this paragraph formed an interesting basis for the design of the motivational aspect of E-quarium. From the research that was brought up here it can be concluded that relatively simple interfaces can already have an impact on the user.

As stated, it was important to create a strong emotional bond between the user and his personal energy coach (i.e. the fish) to garner trust (4.2). This trust could then be leveraged to increase the likelihood that the user would follow the advice and the tips the fish will provide in regards to energy saving. It was hypothesized that the visual appearance of the anthropomorphic agent could play an important role in creating a connection between the user and the fish. There is little research to verify this hypothesis, however intuition dictates that users would feel a stronger attraction to a character that is likable and aesthetically pleasing. This has led to a cute and cartoonish design for the main character, instead of a more realistic (closer to nature) looking fish, which would not be endearing to most users.

4.5.2 Gamification

Games are a part of daily life and always have been. Designers have yet to utilize the full power of games as a medium to tackle a variety of problems. For the purpose of exploring the concept of gamification, the definition given by Salen and Zimmerman will be used (Katie Salen, 2004):

“A game is a system in which players engage in an artificial conflict, defined by rules, that result in a quantifiable outcome.”

When designing a game, the first step is to design the actual challenge. In E-quarium there are actually two challenges, there is the obvious challenge of keeping the ecosystem in order and the fish happy and healthy (4.5.1), but of course this is merely an abstraction of the actual underlying challenge of improving energy efficiency. In that sense the challenge is multilayered. One might ask why this multilayered approach is necessary in the first place? Isn't improving energy efficiency enough? Well as was discussed earlier in this chapter improving energy efficiency, although definitely a challenge, is not very rewarding or fun for that matter. The E-quarium adds a fun layer over the challenge of improving energy efficiency. Traditionally most gamification is more about learning and generating awareness. The game itself is in that case indirectly connected to the goal, in other words the user learns something which can be put into practice to achieve the actual goal (see figure 34 for example).

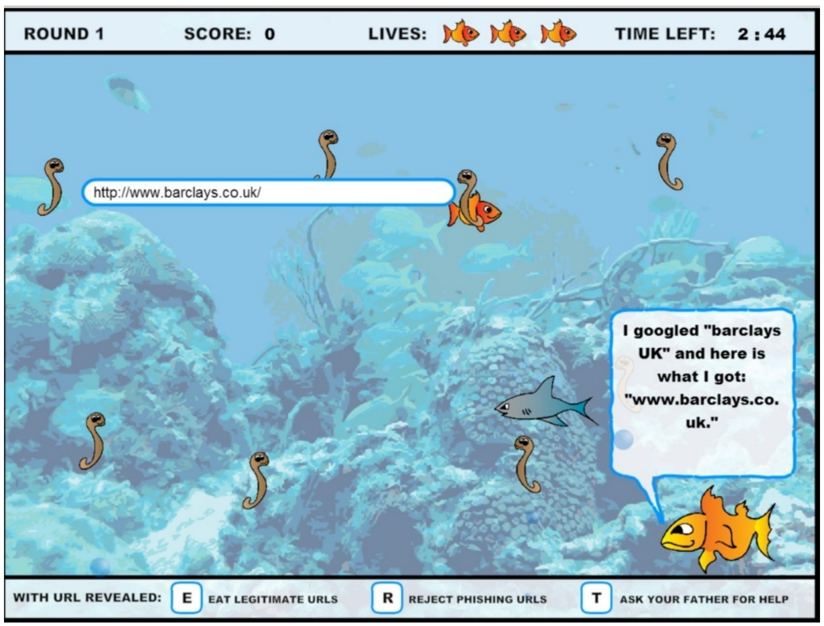


Figure 34 Anti-Phishing Phil is a cyber security game to teach users about phishing attacks. While traditional learning materials fall short either due to their theoretical nature or the fact that users simply aren't engaged. Anti-Phishing Phil showed definite potential in user studies. Sheng et al. (2007)

In the case of E-quarium in-game performance is directly correlated with the actual goal of improving energy efficiency. While teaching and generating awareness are interesting avenues for gamification, the biggest challenge for gamification is to make tasks and processes, that are not inherently fun and engaging, fun and engaging. The abstraction that is made from efficient energy usage to managing an ecosystem and taking care of a virtual pet is an attempt to do just this. More specifically an attempt to increase the amount of intrinsic motivation that is experienced by the user. Which motives are available is a research topic in itself. For the purpose of this thesis the model put forward by Reiss seems more than adequate (Reiss, 2004).

Table 1
Reiss's 16 Motives

Motive name	Motive	Animal behavior	Intrinsic feeling
Power	Desire to influence (including leadership; related to mastery)	Dominant animal eats more food	Efficacy
Curiosity	Desire for knowledge	Animal learns to find food more efficiently and learns to avoid prey	Wonder
Independence	Desire to be autonomous	Motivates animal to leave nest, searching for food over larger area	Freedom
Status	Desire for social standing (including desire for attention)	Attention in nest leads to better feedings	Self-importance
Social contact	Desire for peer companionship (desire to play)	Safety in numbers for animals in wild	Fun
Vengeance	Desire to get even (including desire to compete, to win)	Animal fights when threatened	Vindication
Honor	Desire to obey a traditional moral code	Animal runs back to herd when stared at by prey	Loyalty
Idealism	Desire to improve society (including altruism, justice)	Unclear: Do animals show true altruism?	Compassion
Physical exercise	Desire to exercise muscles	Strong animals eat more and are less vulnerable to prey	Vitality
Romance	Desire for sex (including courting)	Reproduction essential for species survival	Lust
Family	Desire to raise own children	Protection of young facilitates survival	Love
Order	Desire to organize (including desire for ritual)	Cleanliness rituals promote health	Stability
Eating	Desire to eat	Nutrition essential for survival	Satiation (avoidance of hunger)
Acceptance	Desire for approval	Unclear: animal self-concept?	Self-confidence
Tranquility	Desire to avoid anxiety, fear	Animal runs away from danger	Safe, relaxed
Saving	Desire to collect, value of frugality	Animal hoards food and other materials	Ownership

Figure 35 The 16 motives as determined and described by Reiss.

It should be noted that based on these 16 motives the conclusion can be drawn that reaching higher energy efficiency does in essence connect with some of the motives such as saving, idealism and in some cases even social standing (e.g. driving an energy efficient car to demonstrate value to peers). The idea behind E-quarium is to add an additional layer to increase intrinsic motivation by adding an element of social contact and care by means of a virtual pet, but also power to influence the ecosystem. While not currently implemented gamification also lends itself quite well to competition and challenge. Challenges would be on the individual level, while competition would allow households to compete with each other. Additional design work is necessary to implement this into E-quarium

While also not currently implemented in E-quarium it would be easy to build in a reward system that would allow the user to decorate the eco-system. An interaction scheme such as this would work well with challenges. For example, when the user reaches a certain energy efficiency goal the user is awarded with points. These points can then be spent in a store where decorative items or different appearances for the pet could be bought.

4.5.3 Context

Perhaps the most overlooked approach in commercially available HEMS is the feature to take the user context into account. In 2.3 the concept of thermal comfort was explored and it was explained that thermal comfort is decided by more factors than just air temperature. None of the HEMS currently available on the market have strategies in place to advise the user to e.g. wear a sweater or increase / decrease the humidity to increase thermal comfort. More complex strategies could include local heating solutions such as a heat blanket, if the user (e.g., an elderly person) is found to be stationary for a large part of the day. The fish on the other hand, being the user's personal energy coach, could engage people to not only make changes to the desired temperature, but also to their own context / environment. No matter how much automation is implemented in HEMS, failing to engage people and their context as part of the interaction scheme would be a terrible oversight.

5 Inform

5.1 Introduction

The hypothesis is that current home energy management systems (HEMS) available in the market today are lacking in their ability to inform users adequately in regards to increasing energy efficiency.

The first paragraphs of this chapter will focus on literature research as well as the creative effort to come up with a theoretical framework that supports the evaluation of existing systems in terms of being able to provide users with information. While in the last paragraph this framework is employed to do a practical review of the methods incorporated in current literature.

5.2 Background knowledge

Correctly assessing all matters energy related requires quite some background knowledge. Most people would easily be able to measure out a liter and give some indication of how a liter of water could be put to use. Water is tangible, something you can see. The same cannot be said for energy. Energy cannot be held, it cannot be seen and that makes energy an abstract and therefore hard to grasp concept to lots of people. Users not understanding units such as a kWh of electricity or 1 m^3 of gas, can stand in the way of providing people with meaningful and actionable feedback on their energy consumption. Part of any HEMS solution intended for users to increase energy efficiency should take this fact into account by providing clear explanations to the user and in a sense educate the user.

Figure 36 Screenshot from a YouTube series, Power Walking (2011), where people on the street are asked to answer questions on energy related matters. Many people have a very limited (practical) understanding of energy.

5.3 Information overload

While some might say that the abundance of information in the digital age is a blessing, there is a significant body of literature pointing out the adverse effects our information society has on individual (as well as organizational) efficacy in dealing with this information. As Feather (Feather, 1994) puts it *"the technological developments of the last 50 years have made more information more available to more people than at any other time in human history"*. Information is not only more available than ever. It is also more obtrusive than ever. Whether we want it or not information infiltrates our day to day lives through a large variety of sources. It could also be hypothesized that at least part of this obtrusiveness stems from the expectation of others that information in whatever form should be acted upon, or at the very least demands an active decision to ignore. There are many signs that people just cannot keep up with the constant stream of information. As is found by Edmunds and Morris (Angela Edmunds, 2020) managers receive too much information, while at the same time there is the strong believe that the information to truly facilitate the decision-making process is often missing.

Although different terms are used to describe the pathologies of information, “information overload” seems to be the most neutral and overarching. Information overload encompasses the external factor of more information available than ever before and the internal experience of feeling overwhelmed. That being said there is currently no common definition. Defining information overload on the basis of the person environment (P-E) model (Richard S. Lazarus, 1984) results in the following definition:

an imbalance between the amount of information (as well as the amount of sources) available or served and ones perceived ability to cope effectively.

This definition will be used throughout this report as the word “imbalance” inspires a clear visual of the design challenge at hand.

One might question what the more important aspect is in terms of information overload, “perceived” ability to cope or someone’s actual ability. Let’s say the amount of information exceeds someone’s actual ability, but not his perceived ability. He might not be able to process the information, but no anxiety would directly result from the information itself. It is no stretch of the imagination to assume that people have an intuitive understanding of the hardships that accompany having to make decisions in an age where information is so abundant e.g. Not being able to take all information into account, not being able to be sure of the validity of information, are only a few examples of the unease that result in information anxiety.

Upon examining the reasons behind the lack of relevant information to support decision making in the world of business Koniger and Janowitz (P. Königer, 1995) have concluded that the structuring of information plays a key role. It is, however, somewhat unclear what the authors exactly mean by “structuring”. According to the authors structure pertains to the process by which information is created, distributed and received. Their work, however, seems more applicable to archival (collections of information) than to the day to day reality of having to deal with information. Within the business context this makes sense, however this paradigm does not seem to translate well to the domestic domain. However, a better answer is to be found in maximizing relevance of information for individual users through creative strategies. Before looking into such strategies it is important to get a more thorough and formal grasp of what information actually is.

5.4 Information hierarchy

The American British author T.S. Elliot (Eliot, 1934) is considered the first person to allude to the existence of a hierarchy of knowledge / information:

“Where is the life we have lost in living?

Where is the wisdom we have lost in knowledge?

Where is the knowledge we have lost in information?”

A number of value hierarchies have been proposed since then such as “signals, messages, information, knowledge” (Boulding, 1955) or “data, information, knowledge and wisdom” (Ackoff, 1989). These hierarchies have in common that the entities within a lower category in the information hierarchy are of relatively lower value, while entities in a higher category offer more value. The idea behind Information hierarchies is that you can take an entity of a lower category and through processing add value and turn it into an entity of a higher category in the hierarchy.

It is interesting to note that information is used as a blanket term to describe the categories within the hierarchy while at the same time information is a category within most proposed hierarchies. To prevent any further confusion on this matter, from here on out the following writing convention will be adhered to:

- **INFORMATION(with all capital letters)** - will refer to the blanket term for all categories within the hierarchy (e.g. data, information, knowledge, wisdom)
- **information** - will refer to the category within information hierarchies.

A well-defined INFORMATION hierarchy will facilitate the evaluation of existing home energy management systems on the value of the INFORMATION they provide, which in turn will help to design better solutions in the future. As such the chosen Information hierarchy will play a role in this design research and needs to be defined as concretely as possible. Mai (2016) rightfully points out that there is no general consensus about the categories in INFORMATION hierarchies and adds that as far as the same terminology is used by different authors, there is also no consensus about the meaning of this terminology. This general lack of consensus, leads to a certain amount of freedom in choosing and adapting a hierarchy that serves the needs within the context of this design research. That being said the Information hierarchy that is chosen has to adhere to the following:

1. The categories within the hierarchy: $\{C_1, C_2, C_3, \ldots, C_n\}$
2. A proper description of the chosen categories such that Information entities always belong to a single category: $C_x \cap C_y = \emptyset$
3. A proper description of how to transform one or more entities of a category into one or more entities in the next category: $\{ f_1(e_x \in C_1) \in C_2, \ldots, f_n(e_x \in C_n) \in C_{n+1}, \}$
4. One or more definitions of the value of a category within the hierarchy.
   $\{v_1(C_x), v_2(C_x), \ldots, v_n(C_x)\} \mid v(C_x) > v(C_y) \Leftrightarrow x > y$

5.4.1 State

Definition: A state will be defined as a property of an object or an event that can (but does not have to) be observed and measured at some point in time. It’s the purest and most ethereal form of INFORMATION.

state(t) = Value of a property of an object / event at some point in time

Discussion: While it’s up for discussion whether state has its place in an Information hierarchy, it could be argued that the state is Information in its rawest form and at the very least a precursor to Information. While Ackoff (1989) does not formally recognize “a state” in his proposed hierarchy, he defines data as “*the symbols that represent the properties of objects and events*”. He apparently does not, as is proposed in this hierarchy, view objects and events themselves as Information.

Example: The actual power consumption of the refrigerator on November 25 at 13:30.

5.4.2 Raw Data

Definition: Raw data will be defined as the recorded observation(s) of one or more properties of one or more sources in its most basic form (a list of properties and values).

$\{\{state_1(t),\ state_2(t),\ \dots\ ,\ state(t)\},\ \dots\ ,\ \{state_1(t+n),\ state_2(t+n),\ \dots\ ,\ state(t+n)\}$

Discussion: Although the process of observing and recording source Information attempts to preserve state, state being analog can only be approximated and never be fully reproduced on the basis of the digital data alone.

Example:

Time	Power consumption (w) of the refrigerator
11/25, 13:30	460
11/25, 13:40	480
11/25, 13:50	450
11/25, ..:..	…

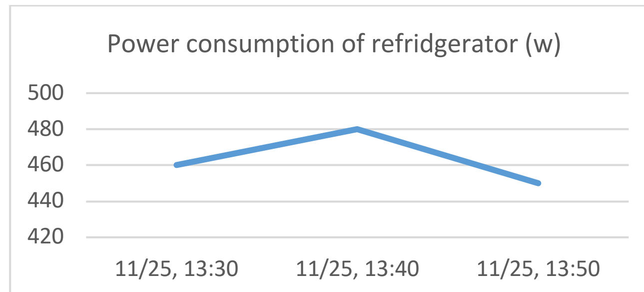
5.4.3 Processed Data (optional)

Definition: Processed data will be defined as raw data on which some (creative) processing has taken place to improve its usefulness and/or usability (e.g. visualizing the data in a line graph).

Discussion: None of the Information hierarchies in literature seem to make an explicit distinction between types of data. That being said the steps that are taken to increase the value of data blur the line between which entities belong to the data category and which entities to the information category considerably.

The lack of an explicit distinction between types of data does not connect well with the reality of consuming and producing INFORMATION. Raw data has no creative process behind it, besides the selection of states to be recorded (and the way they might be recorded). Therefore, raw data requires more of an investment from INFORMATION consumers to be of use. In order to decrease the necessary investment, raw data needs to be processed in a creative way.

Examples:



5.4.4 Information

Definition: Information will be defined as data (raw or processed) processed to answer a question starting with words as “who, what, when, where, and how many”.

Discussion: Ackoff (1989) states that information is the answer to questions starting with “who, what, when, where, and how many”. However in Ackoff’s hierarchy there is no structural difference between data and information, just a functional difference. It could be argued that a lack of structural difference hinders classification. In the hierarchy that is proposed here, information is an answer to a question (i.e. a word, a number or a sentence) while data in most cases, besides those most basic, requires some cognitive investment to find the answer (e.g. interpreting a graph). From an interface design perspective this does mean that designers need to think about which questions are relevant for the end user. Answering those questions that are relevant to users.

Example: On November 25th the maximum power consumption of the refrigerator was 480w at 13:40

5.4.5 Knowledge

Definition: Knowledge will be defined as a proposed course of action on the basis of one or more information entities. Knowledge, as in know-how, will be the answer to a how-to question.

Discussion: Knowledge is the highest category of INFORMATION within the chosen hierarchy. It should be noted that within knowledge the course of action can sometimes be implicit. This is often the case when some type of value judgement is involved. When a system would indicate it is bad leave the refrigerator door open, the course of action is implicit (just close the refrigerator door).

Example: Your current refrigerator is consuming a lot of power. It is recommended to purchase a newer model. This investment would pay off after 3 years.

5.4.6 Hierarchy

Now that the categories of INFORMATION within the hierarchy have been defined, it is time to look at the value axis within the hierarchy as defined in the previous paragraphs:

{state, raw data, processed data, information and knowledge)

In other words what separates the lower categories (e.g. state) from the higher categories (e.g. knowledge). After careful consideration it is important to note that even for a single hierarchy there cannot be a single definition of value. In the following paragraphs a number of suggestions will be made on possible value schemes.

5.4.6.1 Time and effort

Probably the most obvious definition of the value axis of the chosen Information hierarchy is the investment of time and effort. On the one end of the spectrum there is state, which does not require any investment. It just is. While on the other end, knowledge, requires a significant investment of time and effort get from state(s) to knowledge.

5.4.6.2 Actionability

As you move up into in the INFORMATION hierarchy INFORMATION becomes more actionable. You can act on knowledge, while it's impossible to act on raw data, without further processing.

5.4.6.3 Reliability

The further INFORMATION becomes removed from its state category the less detailed information becomes. This inherently means that more trust in the processing effort that has resulted in the Information is required from the perspective of the Information consumer. At the same time the more Information has been processed, the more opportunities there are to introduce error in the Information. With that said processing steps such as aggregating, filtering, interpreting, removing etc. are of vital importance to add value to INFORMATION. In general, it could be said that the less processed INFORMATION is, the more reliable it is or at least the more apparent it's reliability is. This leaves designers with a design challenge: knowledge might be much more actionable than data, but might come at the cost of (perceived) reliability.

5.4.7 Information chains

The term "INFORMATION chain" has been chosen to describe a system in which an entity from one category is transformed into an entity in the next category. The INFORMATION chain includes all elements and processes involved in the attempt to promote the value of Information. Inspecting the Information chains that make up products and services gives insight into their designs, as well as their goals.

5.5 How do commercially available HEMS inform?

When looking at commercially available HEMS it quickly becomes clear that these systems provide mostly processed data and very little actual information.

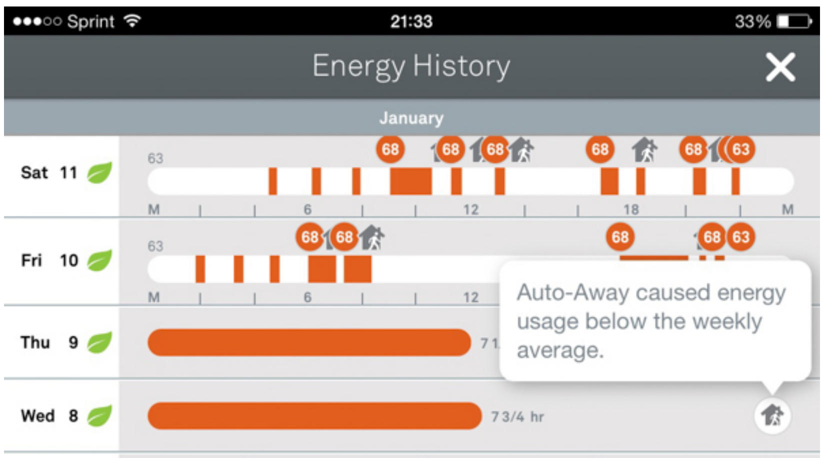


Figure 37 Google Nest Energy History shows the user when the heating system was active through processed data .

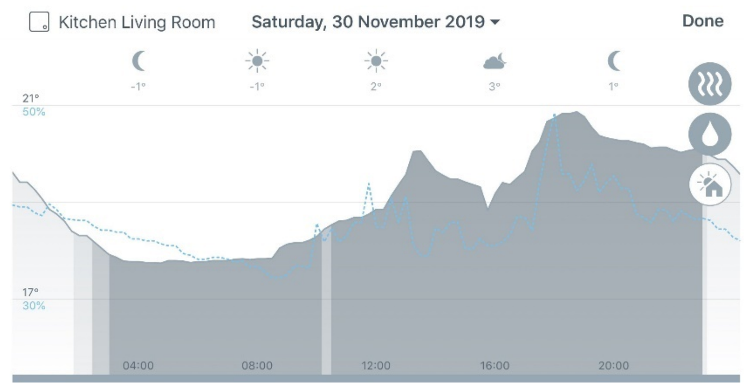


Figure 38 The Tado Grraph shows the indoor temperature (grey line), the humidity (blue dotted line) and the heat requests to the boiler in a single graph (grey area under the line chart). Dragging your finger over the graph provides more detail.

Figure 39 The red line in the Eneco Toon graph depicts the estimated usage by the energy company. That provides some context for the user to determine whether he is doing better or worse than in previous years.

The approach taken by Eneco Toon as shown in figure 39 is actually quite interesting. Through a limited amount of interpretation, the user is able to determine whether he is outperforming the predicted energy usage. A feature such as this is on the right track but still is flawed, since the actual value of this visualization depends on the quality of the prediction. The prediction is merely based on historical usage without taking the current context into consideration. If this winter is much colder than the previous winter than you are likely to overshoot the predicted usage.

Most commercially available HEMS interfaces have a strong focus on processed data, but this can be understood from a design perspective. It is very hard to provide a one size fits all approach to information. A question that is relevant to one user might be irrelevant to another user. This does mean it is left up to the user to transform processed data into information, in other words, providing the user with processed data in theory allows him to answer those questions that he in fact finds relevant. This way of thinking does find its basis in the assumption that people want to and are able to interpret the processed data that is provided. Throughout the design work and the user sessions that were held, it was found that this was not the case. Providing information instead of just processed data is therefore the next challenge for these types of devices. In order to meet this challenge, it is important for these devices to actually get to know the user.

Figure 40 While the number of liters of gas that has been used today meets the information criterium. However, although this answers a question, one could ask whether this information is really relevant to the user?

While not a HEMS in any sense of the word, for the purpose of this research it is interesting to show Oxxio's (Dutch energy provider) take on their smartphone / tablet application. Part of their application is a chatbot called the Energiebuddy 'O'. By adding a simple avatar, the impression is raised that the user is speaking with an actual entity. Because the application is conversation driven (i.e. the user asks an actual question to the chatbot), the interaction scheme is more information centric by nature.

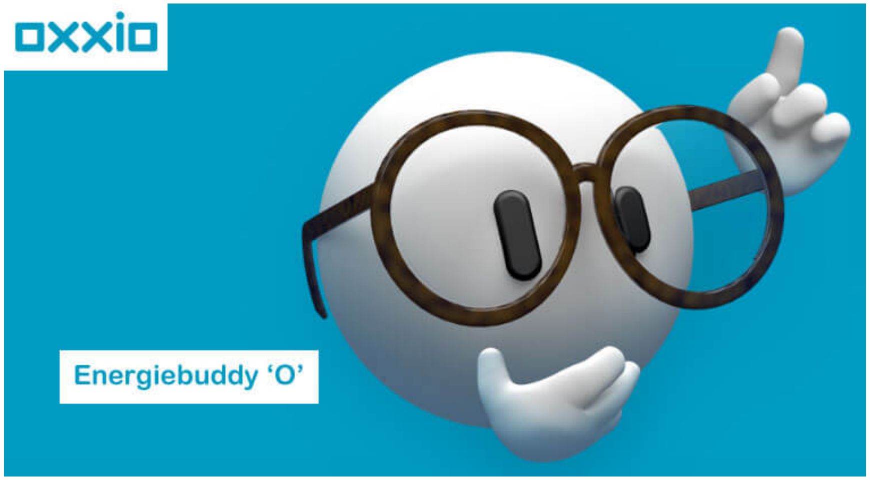


Figure 41 Energiebuddy 'O' has a very simple sphere like design and just two eyes to emote with the user. This simple design also lends itself well for displaying two-dimensionally.

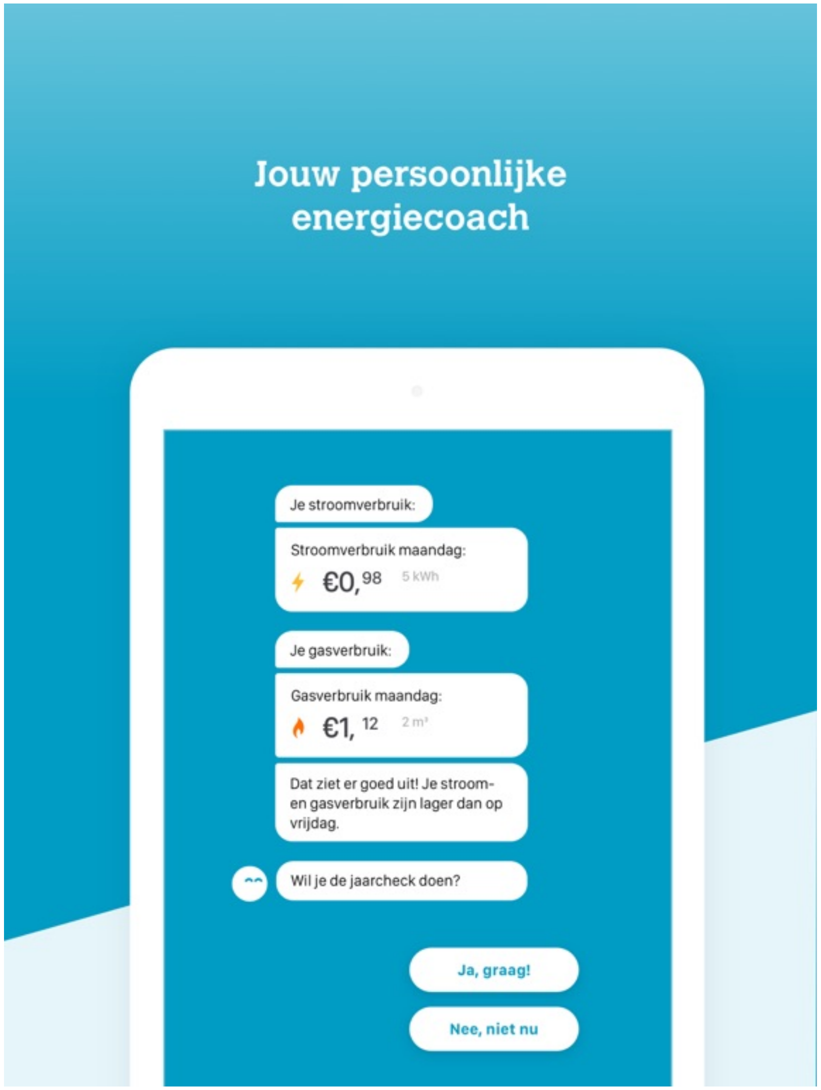


Figure 42 The user can engage in a natural conversation with 'O'. This dialogue style of interacting with the app, can reduce the complexity of the interaction.

5.6 How does E-quarium inform?

5.6.1 Qualification

So what does qualification mean within the context of informing? Well, the basic idea is to omit values and units in the data-centric views by default. For example, in a typical energy consumption graph, it can be read how many kWh were used in the previous month. Let's say the user interprets such a graph and finds out that he used 120 kWh and 100 m3 in the previous month. There are a number of problems here:

1. Electricity consumption is expressed in kWh, while gas consumption is expressed in m3. To show both kWh and m3 in the same graph would not lead to a picture that would do justice to the actual energy consumption. While the amount of m3 of gas is typically lower than the number of kWh. The actual energy in a m3 of gas is much higher than 1 kWh as was shown in the introduction. You could choose to have electricity and gas consumption in two separate graphs, but in the way you would sort of lose the perspective of household energy consumption.
2. A lot of users lack the background information to properly interpret what a consumption data and for very good reason. The typical user might not even be aware of his own consumption data, let alone consumption data of comparable households. So even more experienced users are left wondering what does consumption data actually mean. Questions such as how am I doing are left unanswered and up to the user.

So, the idea is to not show values and units but instead show textual values based on benchmark data, so a user is compared to other households. This allows the user to answer the question how he is really doing in terms of energy efficiency. The most important question a user will always be asking himself, when looking at either raw or processed data will be: Is this good? Or is this bad? That is the information the user is really interested in. By taking the approach of comparing consumption to a benchmark that is somewhat applicable to the user context, this information can be provided to the user. By omitting values and units the background knowledge of the user becomes less of a hurdle.

Figure 43 A mockup of what a graph in E-quarium could look like.

Providing information is just the start, as the holy grail is of course to be able to provide the user with actual knowledge. As an example, the user could find that he is quite inefficient in comparison to comparable households, and the system would propose a solution on how to improve energy efficiency. While in theory this would already be feasible, the large majority of households lack the sensor data to be able to pinpoint such areas for improvement. In the future this scenario is highly likely though as sensors will become less expensive and more ubiquitous.

5.6.2 Conversation

Most of the INFORMATION that E-quarium provides is meant to be conveyed through a dialog interface and not through data centric views. In the E-quarium concept there was only one way communication, but in a later iteration of the concept, that was made as a commercial spinoff to launch the concept into the market, this dialog aspect had further matured.

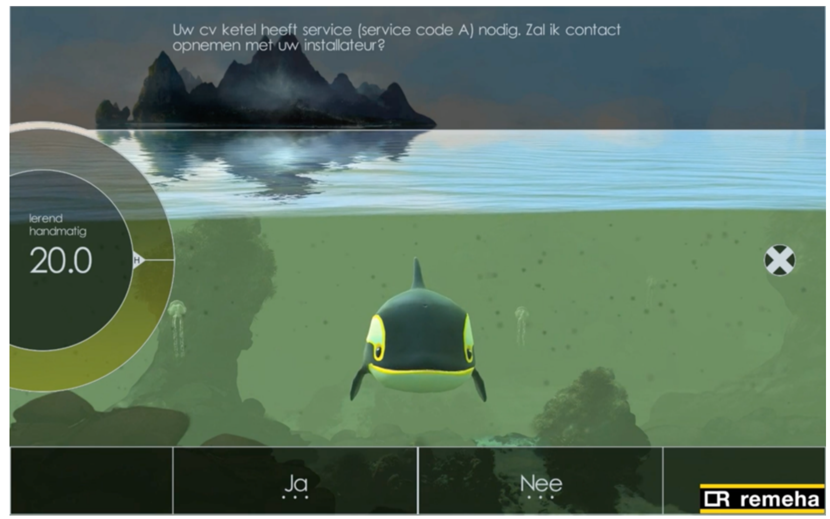


Figure 44 A spinoff concept provided the user with a dialog system which actually allowed the user to respond to his personal energy coach.

As voice recognition and speech synthesis would become better and more common, the plan was always that at some point E-quarium could have made the step to include an actual voice dialog system.

6 Control

A large part of the control that the user exercises over home energy management systems is indirect. There are various ways in which this control can be considered indirect. Just to provide a few examples:

- The user sets up a program and the HEMS then directly controls the heating system.
- In some cases, such as with Google Nest the user does not even have to setup the program, since Nest will just learn the program from user input during an initial learning period.
- Then there are features such as geo fencing which take the geographical location of the user to perform certain actions. For example, if the user gets close to his home the HEMS will set the indoor climate to the desired temperature.

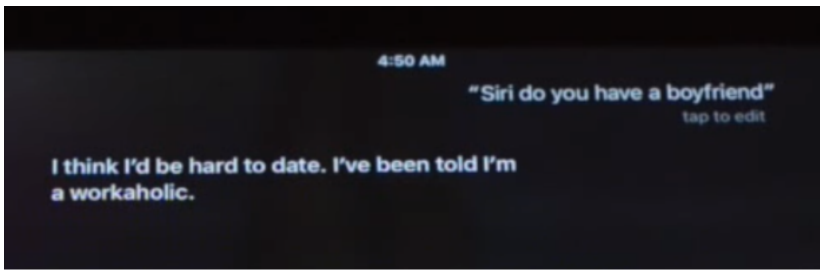
All these features find their origin in delegation. Although most HEMS still offer more direct interaction schemes by having a physical unit on the wall with buttons to receive user input or having an accompanying smart phone app, it was already found in chapter 2 that more direct interaction schemes don't really work in terms of improving efficiency. The manual thermostat is a good example of that. In this chapter the focus will therefore be on delegation and optimizing the experience of a user delegating tasks to a system.

6.1 Voice control

Voice control is all the rage. Google has Google Assistant, Apple has Siri and Amazon has Alexa. Voice control was made popular in modern smart phones.

Figure 45 Siri is Apple's voice assistant running on iPhones.

But voice assistants have also entered the living room space with many physical devices to choose from. With many home devices becoming more feature rich than ever before, it's easy to see why direct control would be hard. For example, a modern smart light is not simply on/off, it has a brightness, a color and in some cases even a program, combine that with the fact that there might be many smart light bulbs in a household and it's easy to see how an interaction scheme might become complex. Especially when there is not just smart lighting but also the thermostat, the air conditioner and many more other smart devices. This makes it easy to see the need for a simple interaction scheme such as voice control. In other words, talking to a device as you would to a fellow human being. This is in part reflected by the naming of voice assistants e.g. Alexa, Siri, Bixby (Samsung). By using person names for the voice assistant, the the impression is enforced that the user is talking to an actual person. To interact with the voice control system the user has to call out the name to activate the assistant by saying something like “Hey Siri” or “Hey Alexa”. Google is the exception to to the rule since their voice assistant is simply called Google Assistant and is activated by saying “Hey Google”. Most commercially available voice assistants such as Google Assistant, Siri and Alexa also provides some answers to questions that are quite irrelevant from a functional perspective but do convey some form of character for the assistant.



Based on these findings it’s not a stretch to say companies want to humanize their voice assistants. Yet the design decision to not incorporate an avatar or face like features appears to be universal among the industry leading voice assistants. Mark Stephen Meadows with a long background in AI is convinced that adding some visual features such as a face or an avatar would increase trust, enhance branding, and improve the efficacy of these interactions (Stuart, 2019).

Figure 46 Amazons smart speaker which includes voice recognition.

Figure 47 Google Nest mini a tiny, fashionable and affordable smart speaker that features voice recognition. It’s price makes it suitable to add voice recognition throughout the house.

6.2 Anthropomorphic Agents

At some point in time anthropomorphic agents were much more prevalent than they are today. It was Negroponte founder of the MIT Media Lab, that said in 1995: "*The future of computing will be 100% driven by delegating to, rather than manipulating, computers.*" In many popular science fiction franchises computers are operated by voice control and have an actual personality. Robots are actually the embodiment of computers that interact with people. Popular culture is actually littered with examples of human like robots to which tasks are delegated. However, when anthropomorphic agents are brought up in this chapter the choice has been made to focus on the digital variant instead of the physical variant (e.g. Android or a Robot). It should be noted that anthropomorphic agents is a made up term as there is variety of terms in literature under which these types of agents are known (e.g. social agents, conversational agents animated agents).

While Microsoft's Clippy the Paperclip may be one of the best-known agents of its kind, this is not necessarily the same as famous. In a sense Clippy is more notorious. In general, Clippy did not prove much help at all to the user and was mostly a nuisance. Clippy autonomously offered suggestions on the basis of user actions, and allowed users to pose questions in natural language and providing the answers that the regular (non-anthropomorphic agent) help wizard would also provide. In addition, Clippy would perform actions on the screen e.g., when a user would click the save button or when idle, Clippy would perform some fun action. It is hard to separate the content and smartness of the advice of the underlying system from the actual anthropomorphic agent. As of the moment of writing AI is becoming smarter and smarter and one can't help but wonder what would have happened if Clippy would have been powered by modern day AI.

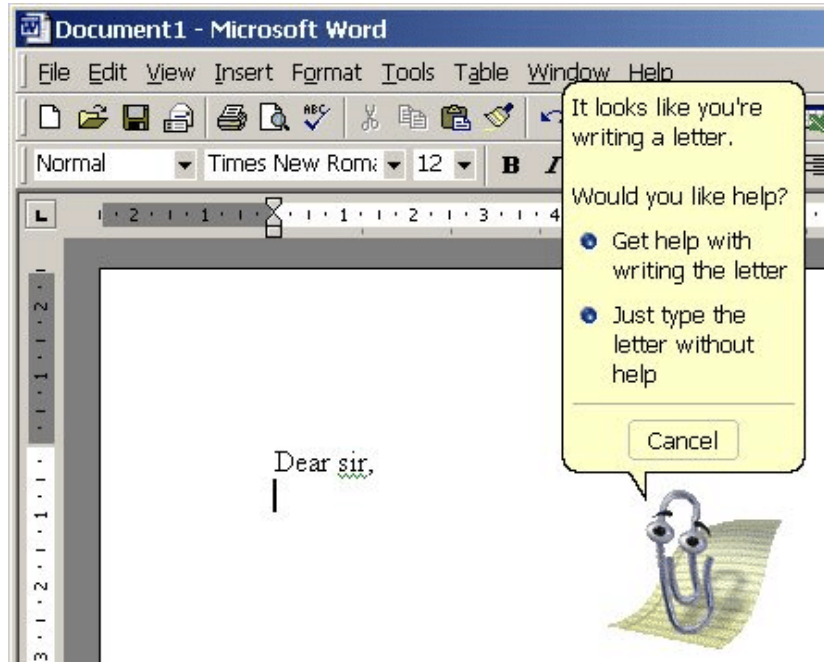


Figure 48 Microsoft Clippy is probably, to this day still, one of the best-known digital anthropomorphic agents in the world.

While it was stated in the previous paragraph, that at least one expert was of the opinion that adding a face to voice assistant would help improve the experience. Research from Nass and Steuer (Clifford Nas, 1993) lists four characteristics that make a human user perceive a computer as a social actor:

1. The use of language
2. Interactivity (does the system base it's actions on the input that was provided by the user)
3. Role (e.g., what role does the system play? A doctor, a travel agent, a friend)
4. Human-like quality of speech

This summation does not give rise to the idea that a face or some other embodiment of the agent would actually be necessary for the user to perceive the agent as a social actor. It is important to mention that the social response to computers is to a large degree unconscious. An anthropomorphic agent would actually make the social response explicit and bring it to the consciousness of the user. Laurel (Laurel, 1990) argues that an anthropomorphic agent can actually make a system become easier to use, since the user is already familiar with the concept of social interaction. Schaumberg (Schaumburg, 2001) concludes that if the social traits of the actor interfere with the reason for interacting with the system in the first place, it will not be accepted by the user. It was found that key characteristics in rejection of the agent-based interface were distraction and trust. In other words, any design that features anthropomorphic agents should make sure that the interaction does not actually become more complicated and tedious by the fact that a button has been replaced by a social actor and the social actor fails to add value.

6.3 Physical position

While it might be tempting to think of a HEMS interface in the form of a wall mounted unit having a physical location somewhere in the house or in the case of multiple HEMS interfaces in multiple locations inside the house, it deserves consideration if that is truly the future of HEMS interfaces. The light switch is a good example, while at some point in time it would have been unthinkable, that the light switch might disappear, in some modern offices this is already the case. If the user wants to interact with the lighting system he can do so through sensors (a movement sensor) or through a smartphone application to set the color or the intensity of the light.

If you look at popular commercially available home smart lighting solutions, it becomes apparent that the physical interface might become less important in the future. Smart lights always need to be powered, traditional switches simply turn the power off or on. This results in the fact that users would not be able to make optimal use of the features that smart lighting offers. With that said most smart lighting solutions do in fact sell physical switches that do work with their smart lighting solution. However, these switches are optional and it might be that there are people that simply opt to control their lights via their smart phone or voice assistant.

Figure 49 The traditional light switch might become a thing of the past in the (near) future.

So where does this leave the HEMS interface? Is it a given that in a few years' time, HEMS interfaces will still be wall mounted units? This might, in fact, not be the case.

Most if not all HEMs interfaces which are available nowadays provide a unit which is mounted to the wall. The question that rises is if this is to truly improve the interaction between user and the system or if it is a commercial decision from suppliers to increase the barrier of entry for newcomers and make sure that consumer data can be harvested. Since even if you would choose to use a third-party smart phone application to control your wall mounted HEMS interface (first party) then in the end data would still be collected. As long as HEMS are actually thermostats most of the time, it is not unthinkable that the boiler will just connect to a sensor network inside the household, without the need for a physical interface due to the fact that the user can simply connect to the boiler and the sensors and directly operate the heating system on his smart phone. In other words, it does not seem like a given that thermostat interface (HEMS interface) and temperature sensor will remain one and the same device.

With the rise of voice assistants, the need for a physical wall mounted unit for control purposes is likely to disappear as the ease of use and the trust in voice control will increase. The question is what this buttonless scheme will do to the user's sense of being in control.

6.4 Autonomous control

Voice control is one way of reducing the complexity that comes with direct control over a system with many options, but it is certainly not the only way. Another trend that can be seen is, that devices become more and more autonomous. In essence not only removing the need for direct control, but removing the need for any control. At least as long as the system functions as intended. For HEMS this is an interesting development because if the HEMS manages to provide the user with an optimal experience (e.g., thermal comfort in combination with energy efficiency) than why would the user even want direct control. Energy management in a sense would then just be one less thing to worry about. In essence there are four characteristics which need to be incorporated in HEMS to provide the systems with a degree of autonomy. It should be noted that not any of these factors alone provides autonomy. To make a system truly autonomous a combination all characteristics is necessary. In the upcoming paragraphs the HEMS will be discussed as if it were a human. While there are autonomous devices that have very little human qualities, home energy management is a complex task because to a degree it even involves user psychology, that the HEMS will have to be able to address to some degree.

6.4.1 Learning

One of the ways that support HEMS becoming autonomous is the ability to learn. One of the ways that a HEMS can learn is by formulating a rule set based on the available inputs and outputs. Let's provide an example. Let's say a user always sets the thermostat to 22 degrees on Saturday 10:00 then the HEMS could learn the following rule "if Saturday 10:00 then set the thermostat to 22 degrees". At the moment learning does not mean much more than trying to learn a typical thermostat program. While this is in itself not revolutionary there is definitely some intelligence involved. Since the user does not have to setup a program anymore and if changes occur to the program the system in theory learns from new user input. However, it was already hypothesized that the cue for a user to interact with a system is discomfort (at least when it comes to thermostats).

6.4.2 Sensing

For a system to be autonomous it needs a way of sensing its surroundings. Sense when to act and a sense of what the result of the actions have been. In the context of HEMS the question can be asked, what is the HEMS actually trying to achieve? Since it would require the HEMS to on the one hand sense the parameters that influence the target state and on the other hand it would need to be able to assess whether the target state has been achieved. If the goal is closely tied to some state of the user, then it would be most important to sense the state of the user, even more important than the state of the surroundings (e.g., room temperature). This shift from sensing surroundings to sensing the user will be the most likely for the home energy management of the future.

Figure 50 The Fitbit smartwatch is able to measure a variety of vitals.

Figure 51 The Apple iWatch also measures the vitals of the user and in addtion provides the user with some basic insight and control without the need for interacting with his smartphone.

A lot of the functionality that fitness trackers and smart watches offer is some form of health tracking. In other words, sensing the wellbeing and the activity of the user. When at some point in time the data, which is collected has enough depth and detail, it could even be used to optimize the energy regulation within the household. To finish this paragraph two simple examples of how HEMS are already incorporating sensing to act autonomously. The first example is how HEMS use a sense of their surroundings to determine an action. The HEMS senses the temperature is below the target temperature and acts by sending a signal to the boiler. Example number two is more about sensing the user. While the HEMS might not be able to directly sense the user, as it is not the HEMS that does the sensing, but the phone the user has on him, which relays location data to the HEMS. When user's phone senses that he gets within a certain proximity of his home, the phone then sends a trigger to the HEMS and the HEMS will control the boiler to start heating up the house, so it will be at the desired temperature when the user comes home. While geo fencing is not the same as presence detection. Presence detection could lead to tremendous optimization.

Sensor networks will start playing an import role in the future, because for a HEMS to be truly smart, they need to be able to combine inputs. So, what if the user is just close to his home but visiting a neighbor, then this relatively simple proximity detection would not work and you would need additional information, such as an appointment in the user's calendar to determine that the user will not be home. Smartness in devices is being able to combine multiple data sources.

6.4.3 Knowing

Why does knowing help the HEMS to perform autonomously. In an earlier paragraph "Learning" was already discussed, however learning is actually quite inefficient and much more complex in nature than knowing. Learning requires a comprehensive algorithm, as well as a complex strategy to adapt what you have learned previously on the basis of current inputs. Knowing on the other hand is quite simplistic, it is just a matter of finding relevant information for the task at hand. An example of knowing could be that the HEMS has data on the optimal indoor humidity spectrum, when the system would then fall outside of the humidity that the HEMS senses. Based on knowing the HEMS can then act to get humidity back within acceptable bounds. This is just a simple example of knowing, but many other insights could be known by a HEMS to make the system smarter, without the need for the need to learn everything from scratch.

6.4.4 Acting

This seems trivial, a HEMS cannot be autonomous, if it is unable to act on what it knows, what it has learned and what it senses. It should be noted that being able to act is not so much a characteristic of the HEMS, but more a characteristic of its surroundings. Do surrounding systems and appliances expose proper interfaces for the HEMS to interact with. In other words, there is not much a HEMS can do to act, when it is surrounded by "dumb" (non-connected) devices. The ability to interface is not only necessary for control, but it is also necessary for relaying data to the HEMS. The relaying of data could for example be used to share usage statistics or consumption data with the HEMS.

What should not be forgotten is the importance of interfacing with the user. The user plays a very important role in energy management as it is the goal of the HEMS to optimize energy efficiency, which should not come at the cost of the comfort of the user or at the very least any reduction in comfort should be acceptable to the user. While in the ideal situation the HEMS would be able to exercise control over the surroundings, the HEMS should and will probably never have control over the user. With that said it has become apparent that an important factor in comfort is the user himself. For example, the types of clothing that the user chooses to wear, his activity level, his psychological state. While control of a HEMS over the user might not be possible, the next best thing is influence. A HEMS should influence the user to make good decisions to optimize energy efficiency. This requires a dialog with the user and has been discussed in the previous chapters on engaging and informing users.

6.5 How do commercially available HEMS offer control?

6.5.1 Smartphone application

Most HEMS available in the market consist of a wall mounted unit and a smartphone application. While the wall mounted unit is likely there to stay for some time, the device specific smartphone application seems to slowly be on its way out. The reason for this has already been discussed in an earlier paragraph. As more and more smart devices are added to the home, it becomes cumbersome to control each individual device with its own specific smartphone application. Google and Apple, being the most popular smartphone manufacturers, have started filling this gap by providing a standard in combination with a single app to rule them all. Apple came out with Apple HomeKit, Google offers "works with Google Assistant". Whether talking about HomeKit or Google Assistant both applications reduce the need (and in some cases even the burden) to start up an individual app for each device that needs to be controlled.

While device manufacturers are working on implementing features to make the devices smarter in terms of control. To be truly smart from a control perspective it is necessary to be able to combine a lot of data from many different sources. The HEMS manufacturer does not seem like the likely party to make the connection with all devices, at least not until the point that there are clear standards in the market on how devices should communicate together. Based on current trends it would seem that HEMS manufacturers will be banished to the realm of just being a hardware provider while the user interacts with the smartphone operating system specific home management app which is closely tied to the voice control that is also provided by the OS of the smartphone. In terms of the framework that has been set out in this chapter the smartphone applications will simply not be able to keep up in the sensing and acting department. Since sensing is an important part of learning, these device specific smartphone apps will be unable to offer the same smart experience that can be brought by OS manufacturers aiming to provide an integral way of managing smart devices in and around the home.

The question then is what device manufacturers do offer in terms of a unique experience that will keep users invested in their specific smartphone application. The answer is that there are very little discerning features among these device specific smartphone applications, that really set them apart. The design of the user interface might be slightly different but all in all these apps are very much the same. It should be noted that very specific hardware features are likely still best operated through the device specific app.

In terms of control most apps offer a way of directly controlling the thermostat, i.e. to be able to deviate from the heating program that has been set, setting up a heating program and configuring some automation features. Google NEST is currently the only thermostat that has a learning feature. How well this learning feature actually works is hard to estimate. Google's own numbers seem to indicate that this feature leads to savings on the energy bill between 8.4% and 16.5%. However, these savings are calculated by comparing with homeowners that just kept their homes at 20 degrees during the day, which is hardly a fair comparison, since a properly setup program would lead to similar savings (even without smart features such as learning or presence detection). In theory a properly setup program would be more efficient, than a program that has been learned due to the fact that some inefficiency is to be expected during the period in which the device is learning.

Figure 52 Tado's smartphone app

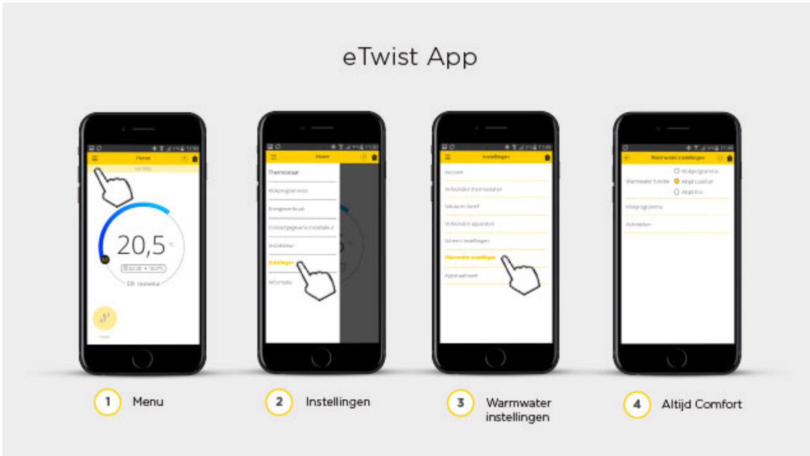


Figure 53 Remeha's eTwist smartphone app

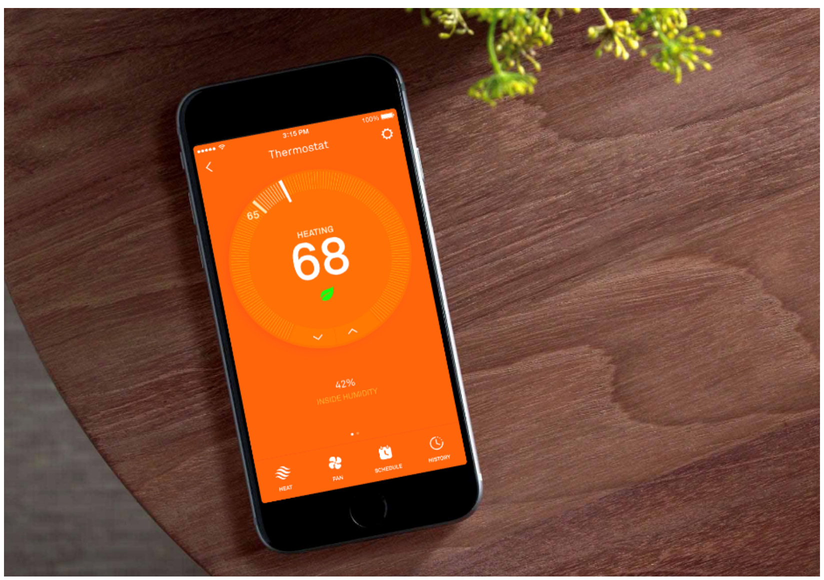


Figure 54 Google Nest's smartphone app

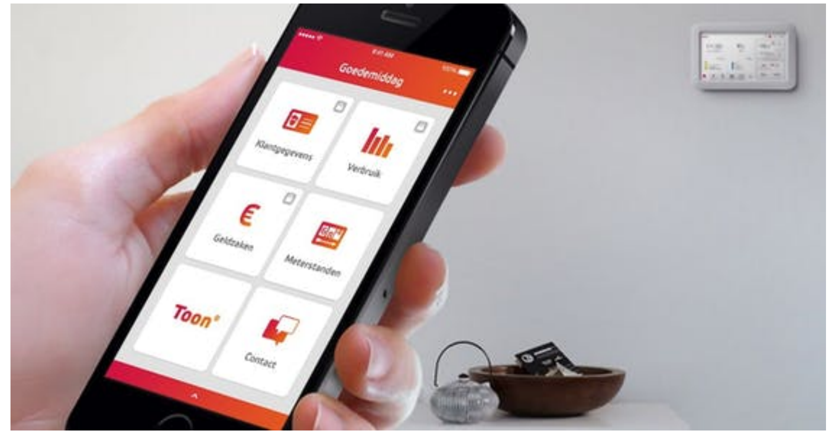


Figure 55 Eneco Toon's smartphone app

6.5.2 Wall mounted unit

From the perspective of the hardware and the user interaction that takes place with the wall mounted unit there are definitely differences in terms of design. Since the thermostat unit will be clearly visible on the wall this is likely to be of influence for users making the purchasing decision. It is interesting to note that most manufacturers have kept a very clean and simple interface, not providing much (if any) screen real estate. Eneco Toon is actually quite different from the norm of simple and clean, as it provides a relatively large rectangular screen on which a much more data-oriented interface is shown. The Eneco Toon wall unit even allows you to control smart lighting and, in that sense, it is more of a hub.

A question that could be asked is how often the user actually physically interacts with the HEMS, when he probably has his smartphone within arm's length and can easily adjust a setting without having to walk over to where the hardware device has been mounted. As HEMS become more autonomous, it is likely that at some point there is no real need any more for mounting these types of devices to the wall.

As far as these devices have a reason of being, it is more likely that the hub like interface will be the future, as it would simply be an overload to have a separate hardware interface for each and every smart device.

Figure 56 Google Nest's wall mounted unit

Figure 57 Tado's wall mounted unit

Figure 58 Remeha's eTwist wall mounted unit

Figure 59 Eneco Toon's wall mounted unit

6.6 How does E-quarium offer control?

The E-quarium system relies heavily on the implementation of an anthropomorphic agent in the form of a fish that acts as your personal energy coach. While E-quarium does offer options for direct control when the user taps the screen (metaphor for the aquarium glass), the fish swims up to the user and offers him a variety of menu options.

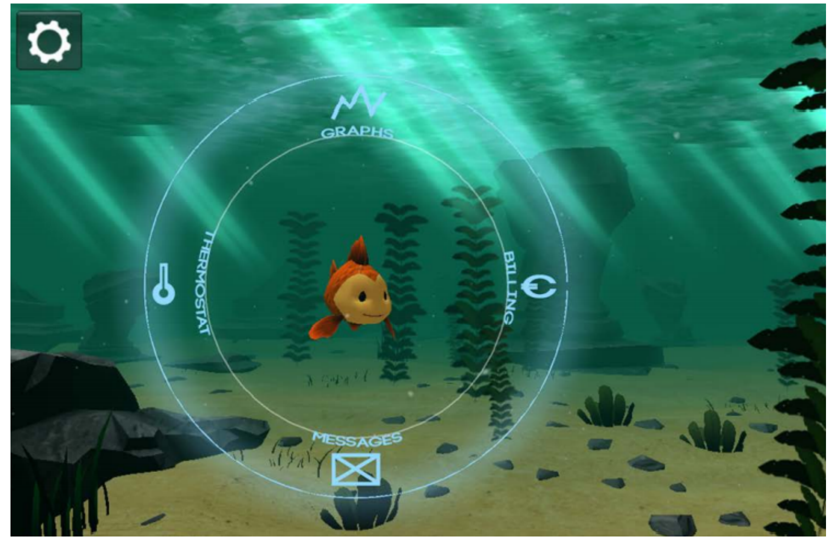


Figure 60 Direct control menu inside E-quarium pops up when the user taps the screen.

The idea behind E-quarium was always that at one point in time voice control would become the standard. Then the user would be able to directly talk to the fish. Instead of talking to an empty screen the user would gain the sense that he would be talking to the fish which should feel more natural. It is not a given that this is a winning strategy and requires further research. There are no examples at hand where anthropomorphic agents have led to market success. However, that could easily be due to the fact that graphics, but more importantly artificial intelligence wasn't yet up to the level that anthropomorphic agents were really feasible. An important factor in the adoption of voice control and anthropomorphic agents lies in the complexities of direct control. In other words, the more devices become smart, the harder it will become to control each device individually in an optimal way.

7 Conclusion and recommendations

The goal of the thesis has been to address the following topics:

1. A detailed description of the original E-quarium design.

2. A description of the research that explains the necessity of the design, substantiates the requirements that were set for the design and argues and evaluates the choices that were made during the design process.

3. The final design will be placed within recent development in the field of user interfaces and home energy management.

The choice was made to not address these topics in a sequential manner, but instead choose a structure that more closely matches the goal of HEMS interfaces and more importantly focus on those factors that influence the efficacy of HEMS to reach this goal, i.e. the ability of HEMS to Inform, Engage and provide the user with Control.

In conclusion it was found that commercially available HEMS interfaces might offer the user a good level of control, but in general fall short of informing and engaging the average user in a way to optimize energy efficiency. It might be that the focus on control and automation of control is a backlash from the decades of poor UX that was typically found in thermostats. The Nest thermostat, which can be regarded as one of the first commercially available smart thermostats, has only been introduced in 2011. Taking into account the average lifespan of a thermostat of 10 years (Sperr, 2020), we are not yet at a point that many people are buying smart thermostats to replace an older smart thermostat. Instead a more likely scenario is that consumers are looking to replace their old thermostat for the simple reason that it offers either not enough functionality or is complex to operate. When the reason for replacing the old thermostat is poor UX, then from a commercial standpoint it makes sense for HEMS manufacturers to lay the emphasis on UX, but also what the hardware unit looks like on the wall.

For commercially available HEMS, the goal of optimizing energy efficiency seems to have been second to improving UX, which has led to better UX (Ruth Tamas, 2021) and some savings. In designing the E-quarium the focus was on optimizing energy efficiency first and design a UX to support that goal. Not surprisingly, this has resulted in the fact that the UX of E-quarium differs widely from commercially available HEMS. While it could be argued whether E-quarium is the best strategy for helping households to improve energy efficiency, it does highlight the shortcomings of existing HEMS in regards to optimizing energy efficiency especially in the areas of informing and engaging. Perhaps now that climate panic is reaching an all-time high and the pressure to optimize energy efficiency becomes more apparent, we will start seeing devices that put a stronger emphasis on including the user and his context by focusing on better strategies for informing and engaging the user. With that said, it is not unlikely that the push towards automation and sensor networks continues to decrease any need for active user involvement. Although such a strategy in the short run, might not lead to the optimum energy efficiency, as more and more sensors will be available and affordable and more and more data will become available as a result, automation will at some point be the most viable and effective strategy for optimum energy efficiency for the user.

When the user is not actively involved in control, this, to a degree, relieves the need to inform and engage the user. Until the right level of data is available (and it's hard to predict when this will happen) the strategies that have been discussed in this thesis to inform and engage, have potential for improving energy efficiency remain relevant.

8 References

Ackoff, R. (1989). From data to wisdom. *Journal of applied systems analysis*.

Angela Edmunds, A. M. (2020). The problem of information overload in business organisations: a review of the literature. *International Journal of Information Management, Volume 20, Issue 1*, 17-28.

Baas, M. D. (n.d.). *73 procent Nederlandse huishoudens heeft een slimme meter*. Retrieved August 16, 2021, from Solar Magazine: https://solarmagazine.nl/nieuws-zonne-energie/i20198/73-procent-nederlandse-huishoudens-heeft-een-slimme-meter

Boulding, k. E. (1955). Notes on the information Concept. *Explorations, 6*, 103-112.

Clifford Nas, J. S. (1993). Voices, boxes, and sources of messages: Computers and social actors. *an Communication Research, 19(4)*, 504-527.

Condry, C. (1978). Intrinsic motivation and the process of learning.

Dillahunt, T. (2008). Motivating environmentally sustainable behavior changes with a virtual polar bear.

Eliot, T. (1934). *Choruses from The Rock.*

Energy consumption in households. (2021, June). Retrieved August 2021, from Eurostat: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_consumption_in_households#Energy_consumption_in_households_by_type_of_end-use

Feather, J. (1994). *The Information Society, A study of continuity and change.* Facet Publishing.

Fernando J. Ballesteros, V. J. (2018). On the thermodynamic origin of metabolic scaling.

Haiying Wang, L. L. (2020). Experimental investigation about effect of emotion state on people's thermal comfort. *Energy and Buildings*.

Helen Stopps, M. F. (2021). Residential smart thermostat use: An exploration of thermostat programming, environmental attitudes, and the influence of smart controls on energy savings. *Energy and Buildings*.

James Jeng-Weei Lin, S. L. (2006). Fish'n'Steps: Encouraging Physical Activity with an Interactive Computer Game. *biComp 2006: Ubiquitous Computing, 8th International Conference, UbiComp 2006.* Orange County, CA, USA.

Katie Salen, E. Z. (2004). *Rules of Play: Game Design Fundamentals.* MIT Press.

Kohn, A. (1993). *Punished by rewards: The trouble with gold stars, incentive plans, A's, praise, and other bribes.* Mariner Books.

Laurel, B. (1990). *The art of human-computer interface design.* Addison-Wesley.

Liang Meng, Q. M. (2015). Live as we choose: The role of autonomy support in facilitating intrinsic motivation. *International Journal of Psychology Vol 98, Issue 3, Part 1*, 441-447.

M. Fountain, E. A. (1993). Air movement and thermal comfort. *ASHRAE Journal* , 26-32.

Maohui Luo, B. c. (2016). The underlying linkage between personal control and thermal comfort: Psychological or physical effects? *Energy and Buildings*, 53-63.

Nobuko Hashiguchi, Y. T. (2009). Effects of low humidity and high air velocity in a heated room on physiological responses and thermal comfort after bathing: an experimental study. *International journal of nursing studies*, 172-180.

P. Königer, K. J. (1995). Drowning in information, but thirsty for knowledge. *International Journal of Information Management Volume 15, Issue 1*, 5-16.

Randall, L. (2017, September 09). *A Comprehensive Guide to Home Energy Management Systems*. Retrieved August 2021, from Sustainable Now: https://sustainable-now.eu/guide-to-home-energy-management-systems/

Reiss, S. (2004). Multifaceted Nature of Intrinsic Motivation: The Theory of 16 Basic Desires.

Richard M. Ryan, E. L. (2000). Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *American Psychologist Vol 55(1)*, 68-78.

Richard S. Lazarus, S. F. (1984). *Stress, Appraisal and Coping.* New York: Springer Publishing Company.

Ruth Tamas, W. O. (2021). Residential thermostat usability: Comparing manual, programmable, and smart devices. *Building and Environment*.

Scanzoni. (1979). Entering a bargain with another under risk conditions.

Schaumburg, H. (2001). Computers as Tools or as Social Actors? - The Users' Perspective on Anthropomorphic Agents. *International Journal of Cooperative Information Systems 10(01n02)*, 217-234.

Sivak, M. (2013, March 27). Air conditioning versus heating: climate control is more energy demanding in Minneapolis than in Miami. *Environmental Research Letters*.

Stuart, S. (2019, January 31). *What Would Make You Trust an AI Assistant? How About a Face?* Retrieved from PC Mag: https://www.pcmag.com/news/what-would-make-you-trust-an-ai-assistant-how-about-a-face

Therese Peffer, D. P. (2012). Facilitating energy savings with programmable thermostats: evaluation and guidelines for the thermostat user interface. *Ergonomics*.

Todd Malinick, N. W. (2012). Destined to Disappoint: Programmable Thermostat Savings are Only as Good as the Assumptions about Their Operating Characteristics . *ACEEE Summer Study on Energy Efficiency in Buildings*, 162-173.

Wooley, F. (2018). It’s about time: Earlier rewards increase intrinsic motivation. *Journal of Personality and Social Psychology, 114(6)*, 877–890.