Technical University of Denmark

Bachelor Thesis (Autumn 2012)

# Building an Intelligent Controllable Home

## For the Solar Decathlon House

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# Preface

This document is my Bachelor's thesis that was created during the summer of 2012 on the department of Informatics and Mathematical Modelling on the Technical University of Denmark. The work for the project itself was initialized in January 2012 and was officially carried out from 01.03.12 to 22.08.12.

This thesis is intended for readers with a software technical background and slightly knowledgeable about home automation appliances. It would also be preferable if the reader has some understanding of software engineering and architecture. This thesis has those subjects representing the main theory and work that has been carried out. Additionally, it would be helpful if the reader is familiar with the various technology, that can be installed in houses.

I would also like to give a sincere thanks to Christian Damsgaard Jensen, who has been the supervisor of my thesis. He has brought guidance to what this thesis should contain. I would also like to thank my project group, in which I have cooperated with the last couple of months.

*On a side note, it would be helpful if the report was read together with the .pdf file, since some of the figures and pictures are best seen on a computer.*

# Indhold

# Chapter 1

## 1 Introduction

This project is part of the Solar Decathlon (SD) Competition (`http://www.solardecathlon.gov/`) that is being held in Madrid of September 2012 and it is regarded as the World Championship of Energy Efficient Housing. The goal of the competition is to develop a house that produces more energy from solar panels than is consumes by the users. The project is also regarded as one of the most prestigious project at the Technical University of Denmark (DTU) to date and it is the first time DTU is competing in the SD competition.

More than a hundred people and several sponsors[1] have been involved in the creation of the house, which has led to the name "The FOLD". The name is inspired from the design, which is based on a single piece of paper being folded into the shape of the house, see Figur 1.

The house is especially unique compared to other houses, since it has several installations with modern technology. All devices in the house can be controlled by the appliances placed in the heart of the house called the *technical core*. It is from here, that all the elements from the house can be controlled e.g. lights, power, windows, heating, ventilation, air conditioning and cooling can all be controlled by the technical core. To control all of the different elements of the house, several components from different sponsors has been used, which may not be able to communicate with each other due to different protocol.

This is not very desirable, because two systems may work against each other. E.g. if the house temperature is desired to be at a state of 21 degrees, then the ventilation system would in most cases cool down the house till 19 degrees, because the lower limit of the conditioner allows this, so that it would not have to keep on running all the time. However, if there is a radiation system as well, that works by the same principle, but instead has a upper limit of 23 degrees, then they will inevitable work against each other and result in wasted energy. So a need for a *Control System* arose, that will make sure that the least amount of energy is wasted. Everything would then be controlled in one centralized system, that has been named *Central Control Unit* (CCU).

One more important factor about the competition, is that all the houses in the competition will be capable of sending electricity back to the power grid (The term used is "The Grid"), which potentially could make these kind of houses produce enough electricity for all other households. Not only would this save people a lot of money from buying electricity, but instead people would be capable of earning money with their solar powered houses.

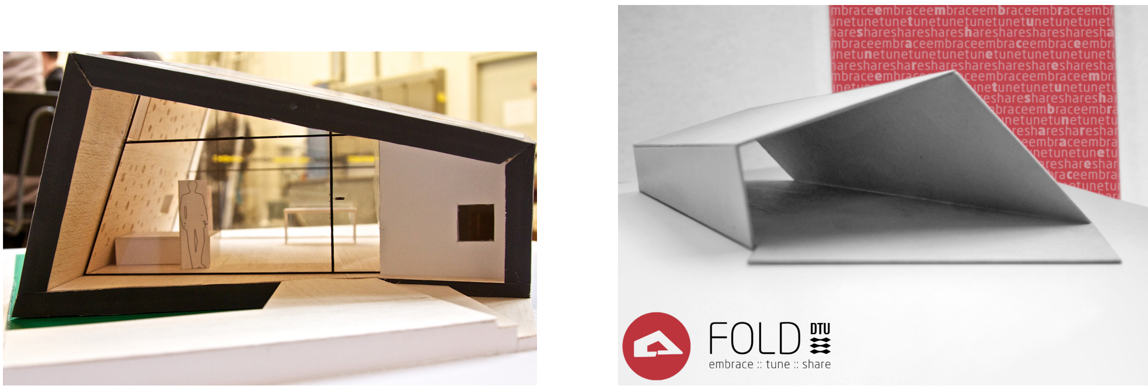
Such systems as this has always been hyped all throughout history. Several appliances has been used to give the title of *intelligence* to houses in the past. E.g. in 50's and 60's houses with control devices,

[1] The sponsors: Grundfos, Danskenergi, Realdania, Rockwool, Uponor, Schneider Electric, Nilan, Velux, Alectia, WindowMaster, Pihl, COWI, RA CELL, Armacell, Henning Larsen Architects

air conditioning, television and advanced kitchen hardware was considered to be the deciding factor on whether or not a house was intelligently built. Later, more appliances arrived such as the microwave, digital devices and more portable appliances arrived, which then became the factor. Today, these things are absolute, because they are everywhere and they are not considered to make any house intelligent. However, the need to help peoples lifestyle has always been popular.

The main goal of this project was to create a system that would intelligently control all the devices of the Solar Decathlon house. The goal of this report is to showcase how Smart houses are categorized and if the Solar Decathlon house really can be categorized as a Intelligent House. The thesis will conclude that this is not the case, but the house is rather a Programmable House with a touch of intelligence.

In the next Chapter, the context of the project will be presented. This includes an investigation of the current understanding of Smart Houses and what it actually means to be become an Intelligent House. A categorized taxonomy[2] will to be used as a definition of what an intelligent house should be. The third chapter will give an analysis of the Solar Decathlon house, that contains the goals for the project and will give different proposals on how to solve the project. The fourth chapter will give an evaluation of the Solar Decathlon house and discuss how the house and taxonomy relates to each other. Finally, conclusions will be presented, that will summarize all the issues previously mentioned.




**Figur 1:** Models of "The FOLD"

[2]http://en.wikipedia.org/wiki/Taxonomy

# Chapter 2

## 2 Context of the project

### 2.1 Introduction

In the modern era and most likely the future we will see intelligent housing become more and more utilized. Most households today already have HVAC systems that might work fine independtely e.g Air Conditioning might regulate the indoor environment, but it does not know if the radiators are switched on nor if any windows are opened. That will of course, result in undesired wastage of energy. Some ideas and solutions have already has been developed to make use of energy more efficiently:

- Intel has developed a energy management system [4], that will examine the current state of the house and give suggestions to the users. This way the users will learn to be more energy efficient and the system will do some of the actions itself to ensure the least amount of energy is wasted.
- There are several solutions on the marked, that have been made to control the smart houses. Some of which are well known commercialized products, today there is WindowMaster [11] and IHC [6]. These system offers possibility for the user to turn devices on and off around the household. E.g. if the house has a Coffee machine which is compatible with the system, then the user will able to start making coffee from their remote control device.

In this project these different kind of systems should be combined, so the user and the control system will make energy efficient decisions together. The challenge is, that the system should not only function with a certain products like IHC or WindowMaster, but it should be capable of integrating with any supplier's control system with minimal effort from the suppliers side. Lastly, the system that should be as simple as possible for the users to gain the advantages of this project's system via an application that is easy and intuitive to use.

The reasoning behind making such a system, is caused by the need to centralize the decision making in the house. Another argument is that it makes peoples life easier and that has always been a popular thing. As mentioned, the different systems will in most cases work against each other and will lead to problems or energy waste. In theory, it could just be a protocol that was built-in in the household devices and simple connected to the internet, so everything could be controlled through the Cloud/internet. However, in this project a centralized server will do just fine, for starters. The vision for the house was stated early on in the process of the project[3]:

[3] In the beginning of the project, our group was supposed to present our ideas at a workshop for our sponsors and the vision of how the system should work was determined there. However, the vision has changed a bit from that perspective till today.

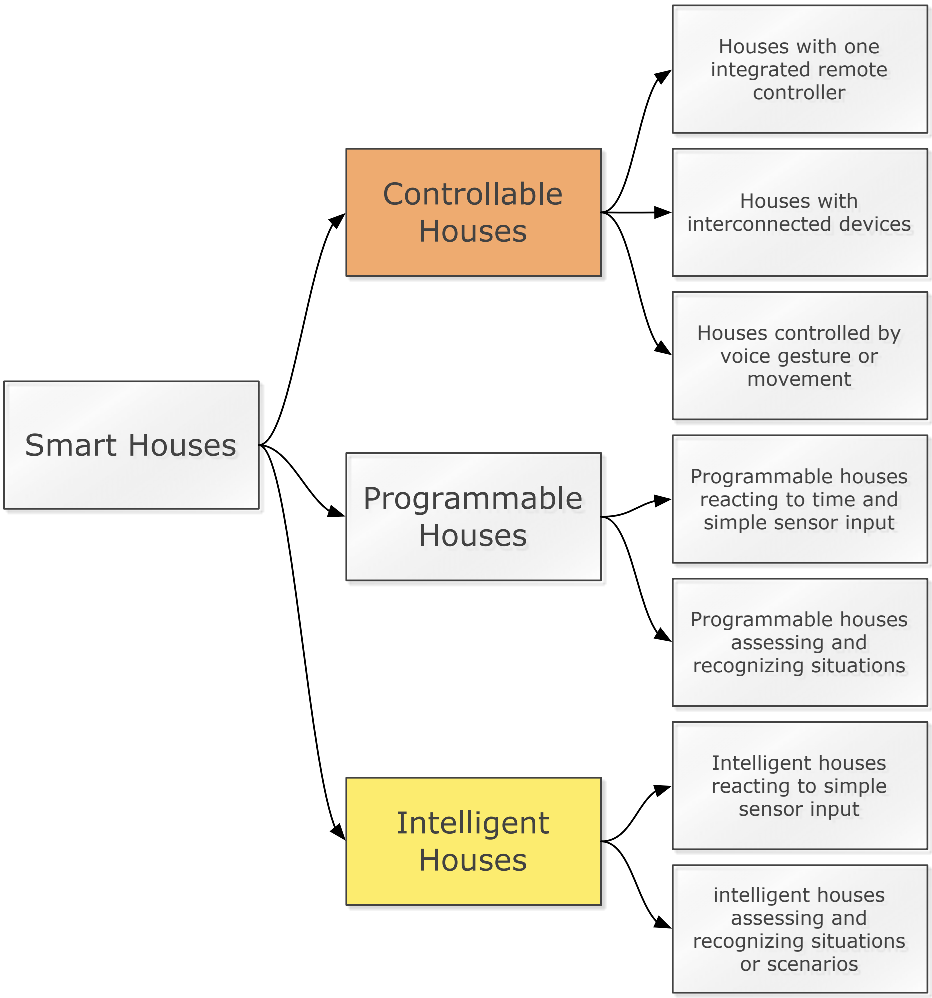
> ”Residents should have to do minimum amount of work to obtain the desired conditions of the indoor environment, whilst consuming a minimum of energy”

The statement embarks the need for a system that will make decision on itself and give the user the opportunity to make some decisions. The system that has been developed is capable of being autonomous and it has also been designed, so that the user can make a lot of decisions themselves as well.

## 2.2 Model for smart houses

### 2.2.1 Taxonomy

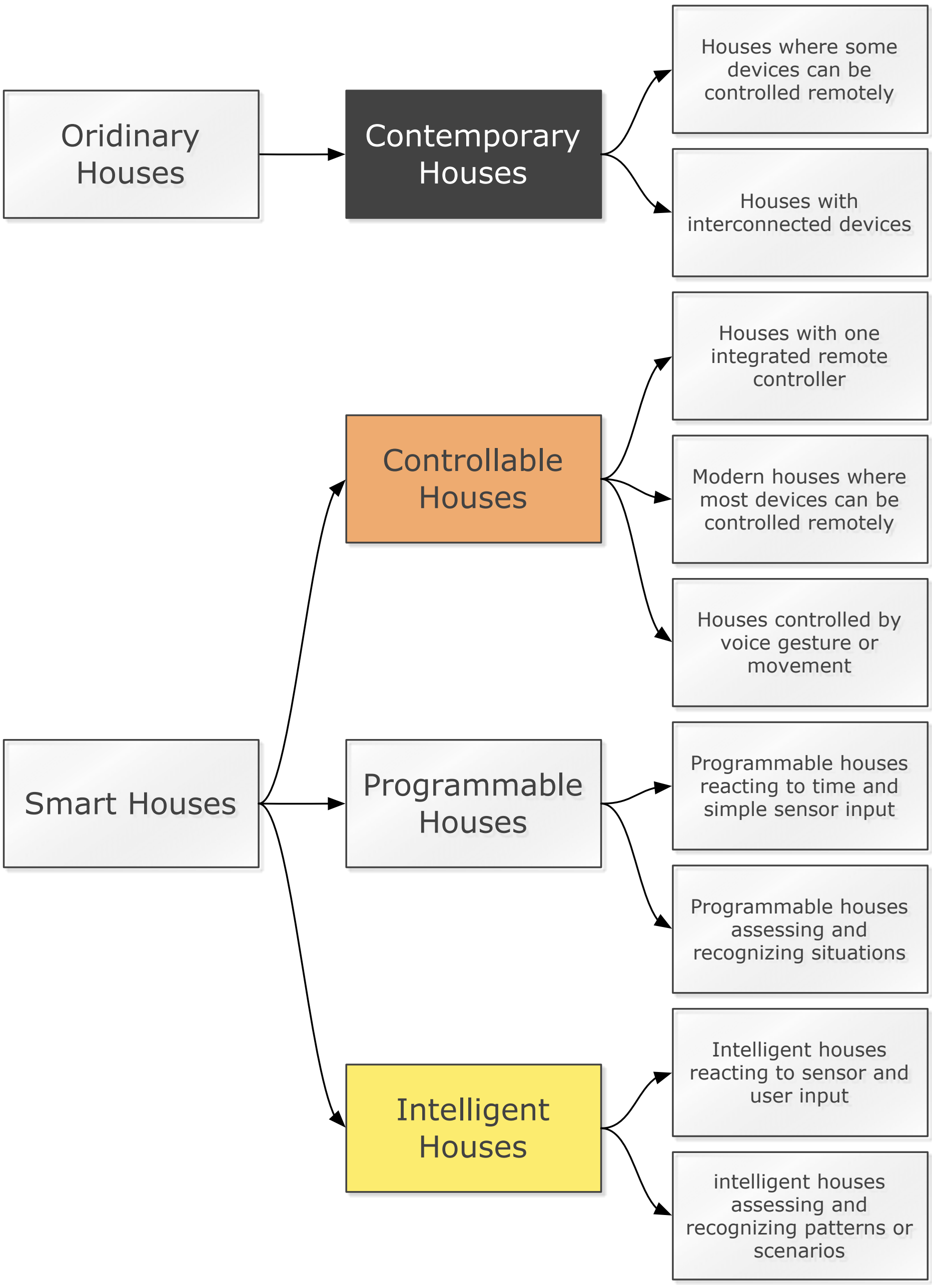
To get a better understanding of what is required, for a house to become ”smart” or ”intelligent”, it is needed to present a model of such houses. To give an evaluation of the solar decathlon house an taxonomy is presented to differentiate all parts of the house, that explains what aspects of people’s life the house improves. An evolution model is presented as well, that will that will explain the advantages and disadvantages from the evolution from being a contemporary house into an intelligent house, established by the work done by Pilich [7]. However, the model of Pilich has been updated, so it follows a more modern perception of Smart Houses. For example, Pilich states that remotely controlled- and interconnected devices is part of the *Controllable Houses*, yet they are so common today, that they should be linked to the *contemporary houses*. Pilich’s original taxonomy can be seen on **Figur 2**, but an extended taxonomy will be presented in the next section.




**Figur 2:** A taxonomy of how smart houses are categorized.

#### 2.2.2 Extended Taxonomy

It has almost been a decade since Pilich made his research and peoples homes has become more advance in general. So an extended version of his taxonomy has been made as seen on **Figur 3**.




**Figur 3:** A extended taxonomy of how smart houses are categorized.

- **Contemporary Houses** is a separate category of homes, that is a ordinary type of house. It is not considered to be part of the Smart Houses in the taxonomy, but it helpful to make clear distinction between them. Some contemporary houses might be deceiving in the sense, that they commercialize themselves as such a Smart House. They only have a few appliances that can be controlled remotely and some devices can be interconnected. The distinct classes have been formulated:
  - **Houses where some devices can be controlled remotely**. In such houses devices like TV sets, timers, kitchen hardware etc. can be controlled remotely. These devices do not offer integration with any system, that might be able to control them.

- **Houses with interconnected devices**. Several electronic equipment such as computers, TV sets, entertainment system, home network can be interconnected. Examples of this could be peoples living room. More and more people are getting more advanced entertainment systems, that can be interconnected by a NAS-server [4], that is able to provide data to all other devices. Boxee [5] is a great example of this, it is able to provide content to the users and gather information from the other systems connected to the network, so sharing becomes easily done.

- **Controllable Houses** is the second category of smart homes. These types of homes offer a improvement in controllable devices. The inhabitant is able to control devices in a more advanced fashion. The classes have been identified for three classes of houses.

  - **Houses with one integrated remote controller**. Having a house with one integrated remote controller requires a whole lot of appliances that are compatible and subsystem that can handle the requests from the remote. However, they are not technically challenging to implement, since they come as finished product from certain manufactures. An example of this could be a remote that would control the in-door climate system while also being able to switch on or off entertainment devices such as TV sets etc.

  - **Houses controlled by voice, gesture or movement.** This infrastructure is partly similar to the previously mentioned groups and classes. The only different is, that all the devices can be controlled my voice control, gestures or movement. Examples of this could be having a motion detector such as a hacked Kinect[6]. Another elaborate example is the voice communication with the system in charge of all devices, such idea has been popularized in the series Star Trek where the star ship Enterprise can interact with the crew.

- **Programmable Houses** allows the inhabitants to have devices react and adjust in certain ways depending on the conditions of the house. Two subclasses have been identified:

  - **Programmable houses reacting to time and simple sensor input**. Using time to allow certain devices to be turned on or off offer a kind of dynamic to houses. Certain appliances can start up early in the morning and others can shut on or off if a specified temperature has been reached. There can also be outdoor sensors that announces if the sun has gone down, so the house will prepare for night. Basically sensors and time are highly reliable, so it is no difficult task to integrate these inputs, but it requires some management of the additional information.

  - **Houses assessing and recognizing situations**. The house is able to recognize certain situation that does not live up to the desired state of the house. E.g. as earlier mentioned if the air conditioning is trying to get the temperature down whereas the radiators are trying to raise the temperature, then it would lead to energy waste. Then the house would turn off one of the devices to avoid these situations. This however requires a reliable software infrastructure, that is able to gather this information, so it can perform the necessary actions.

- **Intelligent Houses** is the final frontier of Smart Houses. This group is very similar to the Programmable houses, however they able to interpret more information types, in a much more complex way due to highly sophisticated software. Two subclasses has been identified:

[4] http://en.wikipedia.org/wiki/Network-attached_storage
[5] http://www.boxee.tv/
[6] Potential use of gesture control in medicine using the Microsoft Kinect camera: http://www.youtube.com/watch?v=b6CT-YDChmE

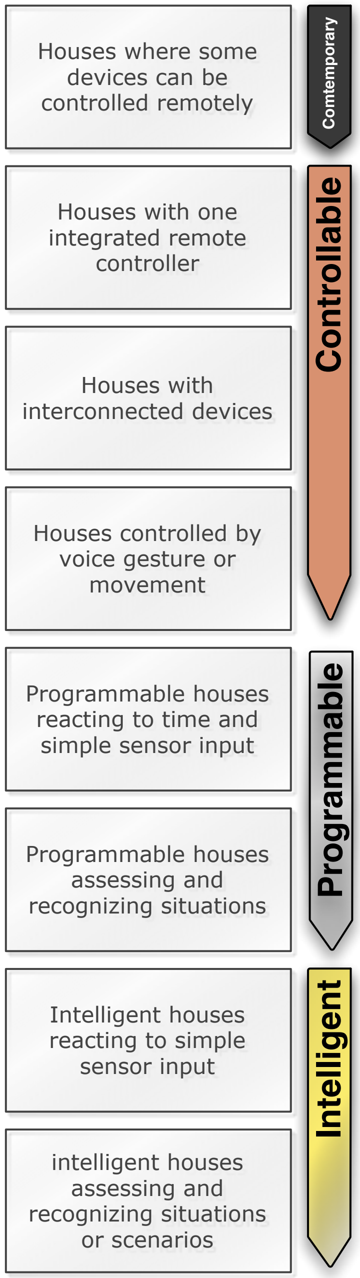
- **Intelligent houses reacting to sensor and user input**. These sort of houses has most of the same appliances available as the programmable house. However, they takes use of the information in a much more interesting matter. These sort of houses are able to interact with the inhabitants in a way that the other types of smart houses cannot. By providing evaluated calculations from the data, the house is able to enquire the inhabitant's attention to decide what needs to be done in order to improve their desired lifestyle. E.g. the intelligent house could provide suggestions for the user, that encourages the inhabitants to save energy and it might then, make their lifestyle are more energy efficient one.

- **Intelligent houses assessing and recognizing patterns or scenarios**. The last subclass is cutting edge intelligent housing that will recognize inhabitants behaviour and use artificial intelligence to make decisions on its own, based on the desired state of the house. By culminating all the previously mentioned classes, these type of house takes into account every parameter it receives and it can adapt to custom scenarios specified by the inhabitants. As an example, if a household has two inhabitants, lets say a male and female, that each has their own desired preferences for how the indoor climate should be. The male prefers a nicely ventilated room with low degrees whereas the female prefers no ventilation at all and higher degrees, the intelligent house would then find a common state of the house, that is in both the inhabitants favour. Some solutions has already been made to do this, where each inhabitant would need to carry a device, that would notify the house which area of the house they were in. Nothing has been successfully commercialized yet though.

## 2.3 Evolution Model for Smart houses

### 2.3.1 Evolution Model

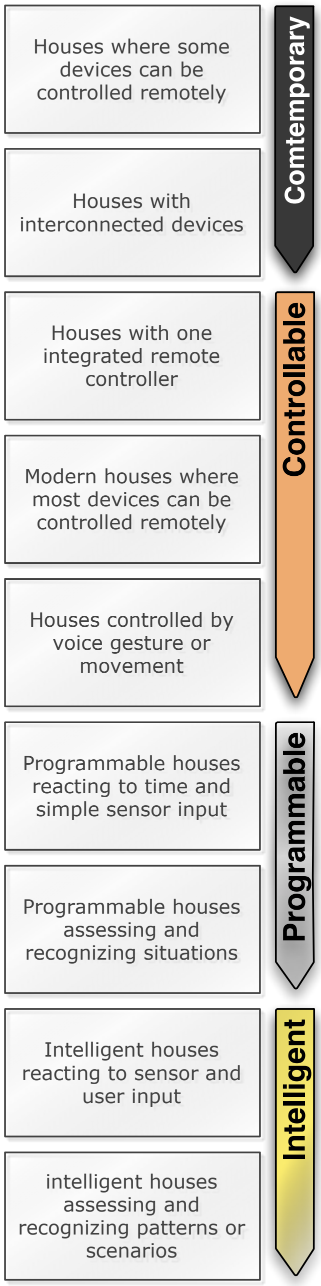
A evolution model established by Pilich will be presented that focusses on the advantages and disadvantages of each subclass from the original taxonomy from **Figur 2**. It is meant to show how the progress through different smart houses develop. The model is meant to advertise what each subclass brings to the inhabitants lifestyles. From **Figur 4** the original model from Pilich can be seen and only here is the contemporary house represented in his work.




**Figur 4:** An evolution model of Smart Houses.

### 2.3.2 Extended Evolution Model

The extended evolution model as an updated version of Pilich's that follows the same subclasses from the extended taxonomy from **Figur 3**. As the final part of this chapter, the evaluation will be presented based on the extended evolution model as seen on **Figur 5**.




**Figur 5:** An extended evolution model of Smart Houses.

### 2.3.3 Contemporary Houses

In the last decade, contemporary houses has changed a whole lot. Many houses now own one or more robots, that is able to perform everyday tasks e.g. the vacuuming robot Roomba[7] and the mowing robot Robomow[8]. These kind of machines has become extremely accessible and practically anyone could install them. Nevertheless, very advanced software and hardware are being used in a very intuitive fashion. They do however have limitations, as they cannot be customized and most of the time, they just function by press-and-play and that also limits their potential. Other household appliances, that is responsible for indoor climate can also be provided as a interconnected package, that is controllable from a remote, but again, they have the same limitations. These products are running within a closed environment, so that nothing can interfere with their system.

The contemporary house is very limited to what the products they purchase. It not always the case, that two systems that the inhabitant initially thought would worked together, actually does. So it can be quite difficult some times, to get a contemporary house where every system works in harmony. Hence, some systems might work against each other, as mentioned earlier.

Just in the last decade, the world has become revolutionized by amazing mobile products such as the portable music player, smart phones and tablets[9]. Evolution in the tech gadget world is going really fast. More and more cloud services are becoming available several times a year now and limitations of electronics is partly being moved to the cloud. The cloud is being used as a method of using external resources to perform difficult tasks. The usage of smart phones to control devices in the contemporary homes, has become possible through the use of *Apps*[10]. This has opened the possibility for devices to become remotely controlled by such applications, instead of the standard remote controller.

### 2.3.4 Controllable Houses

As mentioned in the previous section most houses can control some appliances. However, no complete package has been installed. The Controllable houses offers a single solution, that is capable of integrating with almost any device in the contemporary houses. This makes it very convenient for the inhabitant, since they do not have to keep track of several systems at once, but instead a universal one. The Controllable houses offers a system that can be controlled from a single device like a tablet for instance.

The Controllable houses is even able to control certain items of the house, that normally would not have been e.g. windows and door can be closed or locked by the system, by stalling a component able to perform the task. There is however limitations to the Controllable houses as well. For instance, it is required by every appliance to be compatible with the Controllable houses system. This creates a big barrier for the kind of appliances available and it will probably not be cheap either to integrate in every device on marked.

Besides those barriers for the controllable houses, it is still worthwhile to investigate further. If a universal standard would become available, that could be installed in all devices, making them able to be controlled by the controllable houses, then it would become very convenient for the users. It is one of the major issues and like everything else that improves peoples lifestyle, could become successful.

[7] `http://www.irobot.com/dk/`
[8] `http://www.robomow.com/home.html`
[9] Examples of these could be the iPod, iPhone and iPad.
[10] Apps: An App is short term for application on the smart phone.

Another feature that could be used in these houses is the cloud. However it might seem cleaver, it actually brings a lot of disadvantages as well. What if the house losses the connection? Security and privacy is also at risk and performance might depend on the network. So the Controllable houses might need to have a server placed in the house, that takes care of all the processing of the controllable houses. This could become very expensive i.e. the users would become less interested.

### 2.3.5 Voice, gestures and movement

As presented in the previous section it was discussed how different devices could be controlled in the controllable houses. There is however still more improvements to be made. By comparison of the controllable houses to contemporary houses, a more advanced approach could be integrated in the controllable houses, namely voice, gestures and movement. It is much more intuitive to use voice to control devices, than learning a control system. It is much easier to tell a lamp to turn off, than to first log into a system and find it.

There are however a great deal of disadvantages to voice recognition. Some of the best example of voice recognition today is Apple's Siri and Google's Voice-Recognition[11], that is able interpret sentences and figure out what information is sought. Even though these are the best in the business, they still do not function well enough and certainly not well enough to be integrated in controllable houses. It is however under heavy research and one day it might be possible. Nevertheless, it brings charm and usefulness to the controllable houses.

Besides the advantages and disadvantages, it brings fourth a big technical challenge for the controllable houses. These voice services does not offer house control at all. So a integration with controllable houses will need to be made with the voice recognition systems and this might not be the biggest of priorities by any of the parties.

Movement is another way to control certain aspects of the controllable houses. There are already simple motion detectors installed in many places today, that turns on the specific devices when movement is detected e.g. the light turns on in public bathrooms whenever someone enters. It can also used in the controllable houses to determine what appliances needs to be switched on or off, whenever the inhabitant enters or leaves a room. There are not really any issues nor big advantages in the controllable houses with movement. One small disadvantage could though be pets, they could interfere with the systems, so that unnecessary appliances gets turned on, even though they are not needed.

The last type of interaction is gestures. It has become particularly interesting lately as Microsoft's Kinect has become customizable and it is no longer that difficult to recognize gestures from the users. It offers the same kind of charm and usefulness as voice recognition, but the users does however still need to learn the gestures and it might not be that intuitive to everyone.

By combining these types of human interaction with the controllable houses, it creates a whole new set of challenges for the controllable houses, but also a lot of convenience for the users if the systems work properly. When the time comes, where these problems has been improved drastically, then it will no longer be required to learn the users anything out of the ordinary. It should become as basic as opening a door with your bare hands e.g. a user could point at lamp and call out "Turn this lamp on"or it could even be "Turn on the kitchen stereo and play my favourite album".

[11] `http://forwardthinking.pcmag.com/none/299734-google-s-jelly-bean-voice-recognition-vs-apple-s-siri`

### 2.3.6 Programmable Houses

In the previous category of Smart houses, it was described how appliances of the houses were controlled by the house. A universal solution could be the answer to making such houses. However, it will require immense amount of work spread out on a large number of different suppliers to make it compatible.

The programmable houses offers yet more advances improvements. These type of houses has been brought to life, by having automated processes. The programmable house takes every single sensor input into consideration and decides what actions needs to be done. For instance, the programmable houses is able to control all the HVAC of house, so it can be expected that indoor climate always is being regulated in a desired fashion. Controllable houses are able to detect these sorts of scenarios, but they are not as well executed as in the programmable houses. Hence, the program running in the house has been developed specifically to take care of such things. Instead of the inhabitants telling the controllable houses what needs to be done, then the programmable houses can take responsibility and that relieves the inhabitants a great deal. That results in, improving peoples lifestyle even further.

One great advantage of the programmable houses, is the ability to have awareness of energy usage. This enables the houses to save energy in every decision it makes. It can even consider different solutions to solving an issue and thereby choosing the most energy efficient one. E.g. if the programmable house is being notified that the house is getting to warm, then it has two options: Turn on the mechanical ventilation or open the windows, by evaluating each possibility the programmable houses are able to choose the most energy efficient solution. The programmable houses is also able to keep track of the total amount of energy that has been consumed and produced and in the end, these houses might have saved enough energy, so that the costs of installing such a system into a house has been compensated for.

The great advantage of programmable houses is the assuring of certain tasks being performed. The system will remind users of maintenance jobs and it could even arrange the appointments with the needed maintainers. It is also able lock doors, close windows and shut down all appliances, if no inhabitants are home. Potentially, this could save users a lot of trouble and even a burglary, as is insures the alarm system has been switched on.

The disadvantages and issues with Programmable houses depends on the system responsible for all these different tasks. It could become an extremely complex implementation and yet it could also be very simple. E.g. the house could programmed to just react to certain sensor levels and some specified rules for how it should function. This functionality is pretty straight forward to implement, it only depends on the reliability of getting the correct data and the subsystems working properly. Finally, the programmable houses are able to recognize situations e.g. the houses are able to detect peoples movement and base certain decisions on that.

The biggest hurdle of the programmable houses is the need for a customized solution for each house. It might be possible by the inhabitants themselves, but it is necessarily not always the case. Additionally it would not be able for program running the house to re-program itself, since it is made by a person. Even thought this is minor disadvantages, the programmable house offers a great deal of convenience for the inhabitants.

### 2.3.7 Intelligent Houses

The house of the future is the intelligent houses, that is based on true artificial intelligence, that uses probability, statistics and external resources. They are quite similar to the programmable house except the program is much more sophisticated. In the programmable houses it was a specialist or the inhabitants that needed to adjust the program. In the intelligent houses, it is the program itself, that is capable of learning by patterns. Whenever the intelligent house recognises a pattern, it will add it as an experience in a database and evaluation how this pattern should be used.

The capabilities of the Intelligent Houses are very much the same as with Programmable Houses, but it capable of advantages in optimization. Whenever something needed to be optimized in the Programmable Houses, then a programmer needed to implement that functionality and make sure it functioned correctly e.g. energy conservation. The Intelligent House can learn this process by simple following patterns and instructions, that it was given at the beginning of its *life*.

Another advantage of the Intelligent Houses are the ability to detect if a burglary is being commenced or if an accident has taken place. This is done by simply, not being able to recognize the pattern of the people. In these cases, the system could then notify family, police or neighbours if any of the above had occurred.

The real different between Intelligent Houses and Programmable Houses is the coding and learning algorithms used. It is yet something that is being heavily researched and most likely is not ready to be integrated with intelligent houses at this stage. The system will need to collect data from sensors and users constantly and that require immense processing power including a large storage space for data.

When the time comes, where Intelligent Houses are truly possible, we will undoubtedly see a huge shift in all lifestyles of humanity. The concept of highly advanced artificial intelligence still seems like science fiction today, but it is getting closer within our grasp every year.

### 2.3.8 Interpretation of the evolution model

The evolution model is not supposed to work as a sequence of steps needed to become finally become a Intelligent House. It is meant to focus on what conveniences it brings to each category. The model can however still be used a tool to evaluation, since it presents requirements for each category, that allows houses to be categorized.

## 2.4 Summary

In this chapter a brief introduction of the Solar Decathlon house has been presented together with the vision statement. Next was the work established by Pilich, that has been modified to our present time, with his Taxonomy, that categorizes Smart Houses into different groups of Controllable Houses, Programmable Houses and Intelligent Houses. The contemporary has been presented in the extended taxonomy to give a clear distinction between the different two categories. The categorises of Smart Houses are then used to present an evolution model of the houses, that is used to show how the progress of Smart Houses is being developed. The Evolution model focuses on advantages and disadvantages of each category and how they can improve the inhabitants lifestyle. It can also be used to determine what qualifications is needed by any given Smart House to be placed in one of the categories.

## 2.5 Scope of this report

This thesis will not go into detail with how the implementation of each subsystem has been achieved. It will give an interpretation of what Smart Houses is and how the Solar Decathlon houses relates to these type of houses. In the next chapter, there will be given an analysis of how the Solar Decathlon house. It will establish a foundation of how to build such a system and future teams of Solar Decathlon competition will be able to use this thesis as guidance to building an intelligent controllable system for a house.

# Chapter 3

## 3 Analysis

The analysis will present the goals given by the Solar Decathlon competition and the DTU team. Afterwards possible solutions to the project will be presented.

### 3.1 Goals

The goals of project had been formalized primarily by the DTU team and the people in charge of this project. Some of goals should be able to be recognized in taxonomy from Chapter 1. They are as follows:

- **Controls of all systems**
  Capability of controlling all elements within the house. Some of which can be controlled remotely from suppliers interfaces. The CCU should consist of an infrastructure that supports the same amount of control by connecting all systems together. It was also discussed how gestures and movement could help control certain aspects of the house e.g. some gestures could turn on / off devices.

- **Gather Data**
  Keep record of sensor data and others relevant public information e.g. weather forecasts, local electricity prices etc.

- **Work Autonomously**
  The system should be able to keep the house at some desired preferences while saving maximum amount energy, without requiring any additional input from the users e.g. If it is sunset and air conditioning is turned on, then the CCU could automatically open windows and turn off the air conditioning if the climate allowed so, as long as it preserves the desired preferences.

- **Provide Suggestions**
  By using the current state of the house, the CCU should be notifying the users about what they could do to save energy e.g. If the energy production from the solar panels are running at maximum, then the CCU would suggest the users to do their daily activities such as laundry or mow the lawn with an electric mower, which both consumes a lot of electric power.

- **In-built Preferences**
  The CCU should be able to manage different scenarios of what the user's preferences are. So that each person can have their own preference of house settings depending on their liking e.g. a male user in the house would like to keep the temperature low and with natural ventilation whereas a

female user in the house would like the windows closed and the temperature really high. By the click of a button these preferences should be set into motion.

- **Service Provider**
  The CCU should provide a service that can be used by any application to send commands or retrieve data from the CCU. This enables any application to interact with the CCU and directly gaining access to certain possibilities of the system e.g. most of the internal capability can be called from this service as well.

- **iPad Application**
  An application that is intuitive should be available to the users. It will function like a remote, that uses the provided Service provider to get necessary data and also send out requests to modify appliances. It will also be able to provide statistics and historical data such as energy usage.

Beside the functional requirements, there are some important non-functional requirements for the CCU as well:

- **Integratable with any subsystem (Flexibility)**
  It should not matter if any given HVAC[12] subsystem only provides a specific set of functionality, it should still be capable to be integrate with the CCU.

- **Capable of handling new functionality (Extensibility)**
  If a subsystem provides some new functionality that the CCU is not yet capable of handling, then it should not be difficult for the subsystem to provide integration to the CCU, that the CCU would then be able to handle in an upcoming new version.

- **Only a few steps should be required to integrate a system (Simplicity/Usability)**
  Any subsystem that provides a set of functionality should follow a certain protocol of requirements for that functionality to work with the CCU e.g. Any ventilation manufacturer would be able to integrate as long as they use the same communication protocol with the CCU.

Another relevant factor, is that the Solar Decathlon competition measures on how marketable the house is. So making the systems as simple, beneficial and easy to integrate with any manufactures equipment is a great way of marketing the CCU system and not only using the functionality of the system as an argument.

There are also some non-functional requirements, that are not considered as important:

- **Decentralized system that could be placed anywhere in the world (Maintainability/Cloudability/Security)**
  As long as the different subsystems follow the communication protocols, then it would not actually be a requirement for the CCU to be physically placed in the same house, but instead the subsystem would communicate through the internet and function as a cloud service.

- **Actions are immediately reacted to (Performance)**
  The CCU should not have much delay, so that the correct choices are being decided by the CCU. This is not considered to be any major issue issue, since the server will be within the house and kind of algorithms used in the code will not be very time consuming.

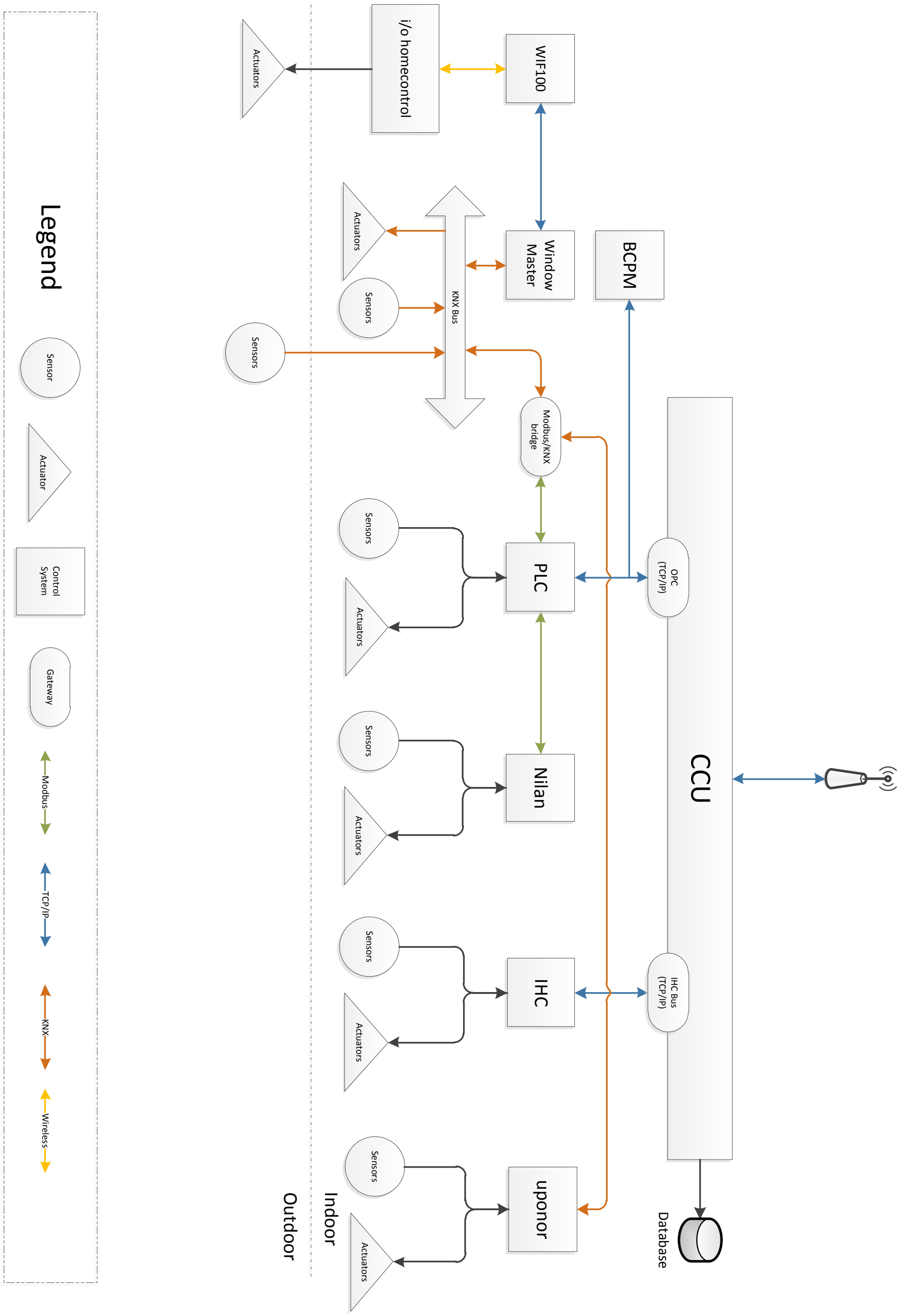
[12] HVAC: Heating, Ventilation, Air Conditioning and Cooling

As for non-project goals (my goals):

- **Be part of something big**
  The Solar Decathlon is a prestigious and very intriguing project that has my own and a lot of peoples interest.
- **See how software and hardware work together**
  During my studies i have not had the chance to use any hardware that was running my own software. It was also very intriguing getting the possibility to collaborate with real manufactures (sponsors).
- **Learn .NET development**
  Since .NET is an important platform in the Enterprise world, I figured it would be desirable to get some more competences with the platform. Also working as a team would give some knowledge as to how software projects should be managed.

## 3.2 Overview of systems, sensors and actuators in the house

The Solar Decathlon house has several different sponsors that provides a wide range of different systems. An overview of how the different systems are interconnected can be seen on **Figur 6**.




**Figur 6:** Architecture of how all the systems are connected

### 3.2.1 Systems

- **IHC**
  Schneider Electric is providing their *Intelligent Home Control* (IHC) system, that is placed in the technical core of the solar decathlon and it will be used to control lights, switches, alarm system and

other actuator devices. The IHC is also going to send some sensor data such as LUX-level, motion detection and smoke sensor. The functionality of the IHC is mostly based on electrical wiring and the infrastructure can also be used to support additional devices in house. The IHC perform these actions by sending out signals to the individual sockets, that controls each device. The IHC was chosen because it offers a lot of flexibility in the kind of devices that can be attached, that has enabled the house to become controllable from a single point.

It will also provide some of the sensor data i.e temperature, LUX, CO2-level etc.

- **PLC**
Schneider Electric is also proving their PLC (Programmable Logic Controller) that communicates via modbus. The PLC is used to control the HVAC system, that controls temperature, heating, ventilation and air conditioning. The PLC does however function autonomously in some of it's decision making. It will automatically regulate pumps, valves and other control devices to keep it's specified indoor climate conditions. It is however still possible to communicate with the PLC and specify what state is should be in e.g. the CCU could inform the PLC to stay at 21 degrees. The PLC has an build-in OPC server, that is used to communicate with the PLC, since the internals of the PLC uses different programming languages. The PLC was chosen because it is capable of controlling the rest of the subsystems such as the Nilan and Uponor units.

Basically, these two systems are the ones that needs to be communicated with by the CCU, to control the rest of the different subsystems:

- **PVT (Solar Panels)**
The Photovoltaic (PVT) is a new form of using hybrid solar panels, that uses liquids to cool down the panels to make them more efficient and also get heated water. It will also be the main attribute of the house itself, hence the name of the competition: Solar Decathlon [10].1

- **Nilan and Uponor Unit (HVAC)**
The Nilan Unit is a subsystem that will adjust indoor climate environment. It is controlling the mechanical cooling system (Air conditioning) and also the domestic hot water tank that is being used to store heat. It can be used to regulate temperature, humidity, CO2-level and mechanical air flow. The Uponor system controls the pumps and valves that is used to transport water throughout all the different elements of the house. It is also used to pump water through the walls of the house to regulate heat. Most of their functionally works autonomously, but it can be controlled by the PLC. They were were chosen because they are very energy efficient and uses cutting-edge technology.

- **WindowMaster (HVAC)**
The WindowMaster system will control the windows and enable natural ventilation to be controlled. It also works autonomously with it's own system, but it can also be controlled by the PLC through a KNX communication bridge.

- **BCPM (Measuring)**
The BCPM is used for measurement of power generation and production. In the intelligent decision, using the measurements can be used to determine how efficiently the house is performing. It can also be used to decide, when is a good time to do certain tasks i.e. if the energy production is running at maximum, then the CCU could inform the user that now is a good time to do some energy consuming tasks such as laundry. The BCPM communicates through an OPC server alike

the PLC.

### 3.2.2 Sensors

Some of the indoor environment values has been set by the Solar Decathlon competition to be at a certain level. The importance of these sensors might not seem obvious at first glance, but they are actually what drives the CCU.

- **Indoor and outdoor climate**
  Of course, temperature is one of the most fundamental sensor types, so it is recorded inside from multiple sensors located in each end of the house, and there will also be an outside weather station for measurements. The temperatures will be used for decision making together with other data types to make wise energy efficiency decisions i.e. If the outdoor temperature is falling quickly, then it would be wise for the CCU to close the windows, so the house would not get too cold.

- **Domestic hot water tank temperature**
  The Nilan unit will control the water tank temperature and there is not much that can be done to increase the temperature, besides making sure that the Solar Panels heats it whenever possible. The water tank temperature is important to keep as high as possible before sunset, so the inhabitants can use it during the night without demanding additional power from *The Grid*. Most of this will work autonomously by the HVAC units, so the CCU just have to keep in mind, that it is wise to keep the temperature of the tank as high as possible.

- **$CO_2$-Level**
  The air quality in the house must be within the permitted limits of the rules and therefore some CO2-sensors has been placed in the house. The CCU can use that data to determine when it should either open windows or turn on the air conditioning.

- **Motion (PIR)**
  The movement of the inhabitants can be used by the CCU to turn of devices i.e. if no movement have been present for a long period of time, then lamp could be turned off.

- **Window and door**
  Will tell the CCU or alarm system what parts of the house is being used, which can be used in decision making as well.

- **LUX**
  The LUX level for lights has also been stated in the rules to be within a certain range. There are two ways of achieving the given LUX level, either by using lighting or removing the curtains. Both of which should be determined by the CCU.

- **Weather conditions** Outside there will be installed a weather station that the CCU can use in it's decision making i.e. if it getting really cloudy, then the Solar Panels will not work optimal, so it might be a good idea if the inhabitants turned off their devices.

### 3.2.3 Actuators

Actuators are household appliances that can be controlled by one of the control systems. Here are some examples: Lights, door locks, windows, blinds, water valves, water pumps etc.

## 3.3 Third-Party Services

As part of the CCU some additional services have been integrated.

### 3.3.1 Calendar

A custom-made calendar will be used to keep track of the inhabitants, which supposedly should be integrated with Google's Calendar by the help of their API[13]. The calendar can be used in the decision making process to check if nobody will be home the following day, so the maximum amount of energy will be saved. It can also be used to prepare the house for when the inhabitants arrives home at a scheduled time.

### 3.3.2 Weather Forecast

The weather forecast is retrieved from a web-service. The forecast can be used to determine what sort of behaviour the CCU should follow. E.g. If dark and cloudy weather is approaching and the house is running a lot of appliances, then it could turn them off and close windows ahead of the bad weather, so the house will keep the desired indoor climate preferences.

### 3.3.3 Sub-summary

A rough overview has been given of the house, that can be used later to categorize the house. It is not needed to go into complete detailed descriptions of how each subsystem functions, since it is the usage of the house, that will evaluated. This thesis is meant to give an interpretation Smart Houses and how the Solar Decathlon house relates to that.

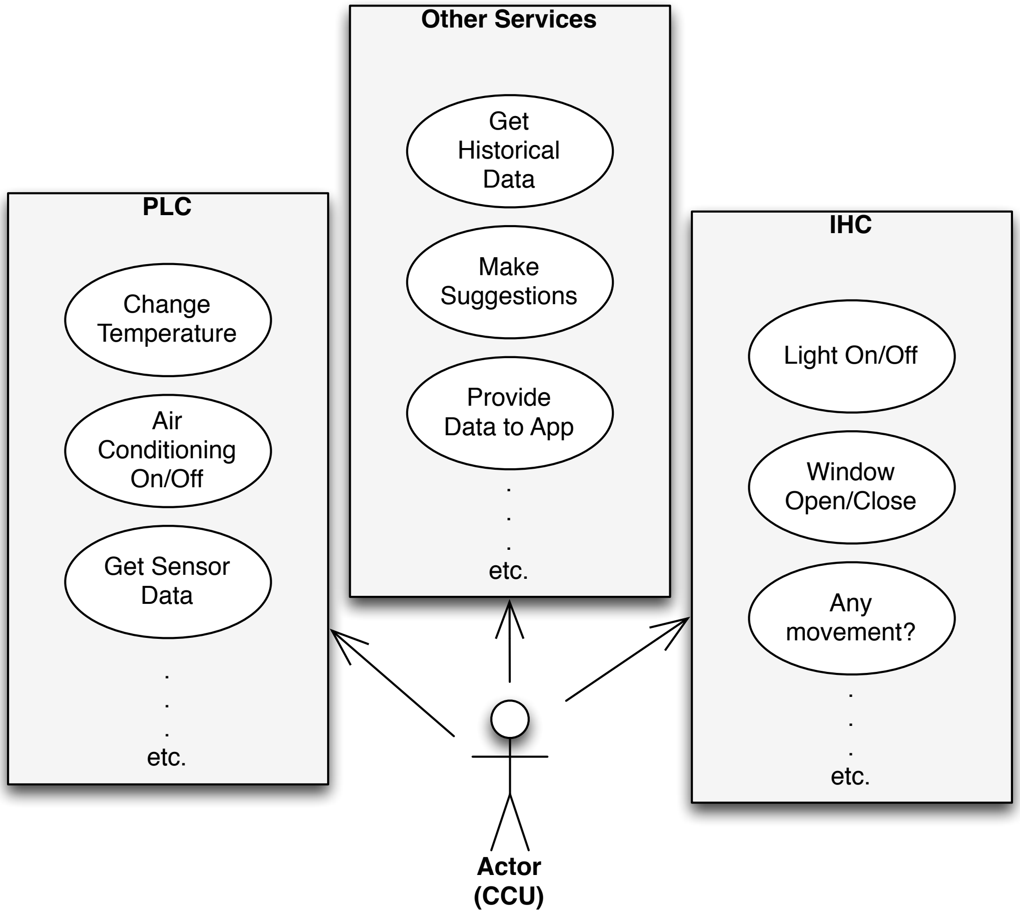
## 3.4 Use Cases

Based on the goals of the project in the given analysis, each of the them can be formalized more relevant to Software Development. Each of the goals will now be categorized and decomposed into what tasks they involved.

UML digrams is useful when trying to get a better understanding of what the CCU is supposed to do. The Use Case diagram is a way of showing the different options available to the CCU and later the discussion of how to get each of them to function will be presented.

[13]https://developers.google.com/google-apps/calendar/

#### 3.4.1 CCU Use Case Diagram



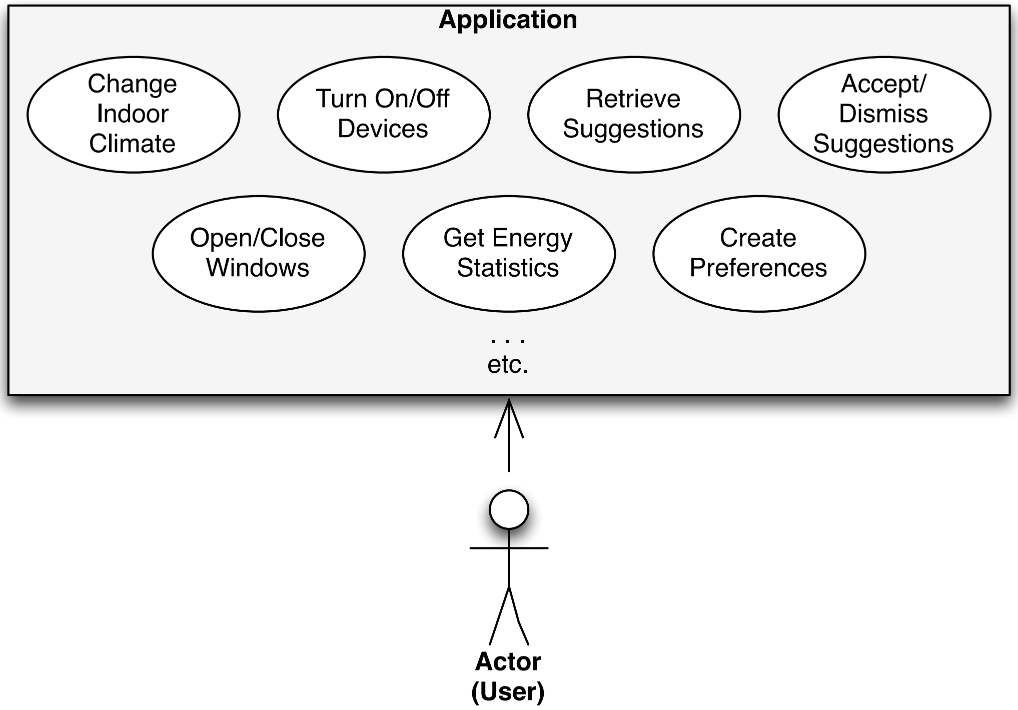

**Figur 7:** Use Case diagram of what the CCU is able to do

As seen on **Figur 7** all the different cases for the CCU are divided into 3 main systems, where the 'Other Services' is actually an arbitrary number, since each case is most likely handled by a new system. A solution to this problem is to make some sort of protocol that would communicate directly to each system and assign a lot of the responsibility onto the CCU itself. By now the term CCU is used in many different connections, but so far it is responsible for:

- Autonomous Decision Making
- Aggregation Point for all subsystems
- Keeping historical data
- Exchange data with suppliers systems
- Keeping user preferences
- Offer application integration

### 3.4.2 User Use Case Diagram

The users of the house would also like to control different parts of the CCU. From **Figur 8** it is possible to get an understanding of the sort of use cases a user of the system would have. More could be added, but it is just to give an idea of what the cases should look alike.

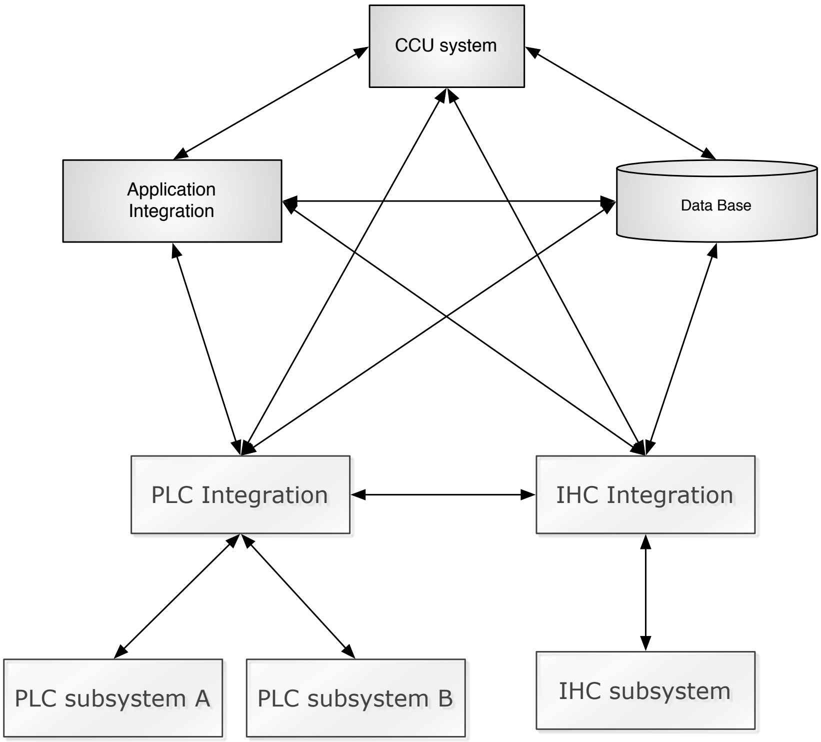



**Figur 8:** Use Case diagram of what a user could be able to do with the CCU.

## 3.5 Architecture

To determine what architecture will be the best solution for the CCU, a couple of proposals will be examined. One solution for the CCU system could have each subsystem integration directly communicating with each other. This would create a kind of fully connected mesh network (topology[14]). As seen from **Figur 9** it creates a lot different communication channels and for every new system that would be added, then a new communication channel for each other system should be made. This will over a longer period of time create an immense network, if new systems are being added too often and will require incremental amount of coding each time.

[14]`http://en.wikipedia.org/wiki/Mesh_networking`




**Figur 9:** A proposal to a CCU architecture.

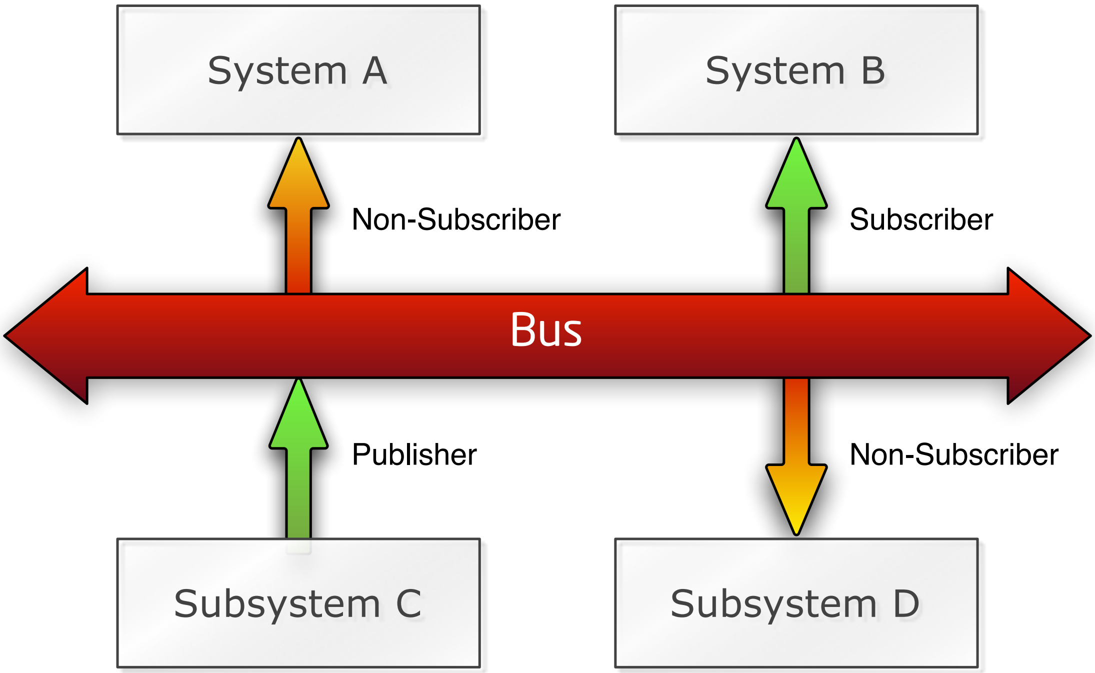
This solution is not sufficient enough for this project then, since it is meant to be a system that should be extendible yet simple. The need for another solution is required.

A universal delivery system could save a lot of time and it would give time more time to work on other tasks. Such a delivery system could be what is known as a Distributed System[3]. The point of using this concept, is to create a sort of communication infrastructure that consists of a Bus Architecture.

### 3.5.1 Bus Architecture

As seen on **Figur 10** the idea of using the bus architecture is that certain parties are subscribed to certain message types and whenever someone publishes something onto the bus of a specific type, only the subscribers will invoke that message. By using this concept no direct links between different system are necessary and this concept will avoid *complexity* and *coupling*, which fits into the model of good Software Development. It also offers benefits in terms of *security* and *simplicity*, since an authentication can take place before communication and the meta-data[15] is also being minimized.

[15] In this case, the meta-data is the information that is being used by the protocol to find it's recipients, namely the message should only contain a type.




**Figur 10:** The concept of a Distributed System as a Bus Architecture. System C publishes a specific message and System B will invoke the message, since it is the only subscriber of that specific type of message

### 3.6 Summary

An analysis of the house has been presented and it helps understand what type of house, that is going to be evaluated. Some of the goals has been presented as Use Case diagrams, that explains what the system is supposed to do from a software perspective. There also been shown proposals to how the architecture should be and the bus architecture tends to be the best solution for this project. In the next section there will be a detailed design description of the control system that has been developed.

# 4 Design

The design section is meant to give an overall description of the developed architecture. The analysis will be used as the foundation for the design.

## 4.1 Components of the CCU

By now, the CCU can be decomposed into different parts. The parts will generally be based on the different use cases for the CCU from **Figur 7**. Each of the goals for the project will be fulfilled, showed by the underlining.

- **Bus**
  The bus concept will used as the aggregation point plus it will do the forwarding of data. By being able to subscribe to certain message types, the bus will allow the different systems to invoke messages. The bus offers both possibility to publish a message functioning as a broadcast, where no response is expected, and it is also possible to publish a message and wait for a response.

- **Central Logic Utility Engine (CLUE)**
  A service will be attached to the bus called Central Logic Utility Engine, CLUE, that will make all of the intelligent decision making by accumulating data and listening to what all subsystems are publishing. It will also be the system that would enable user preferences, since none other system should be requesting many actions.

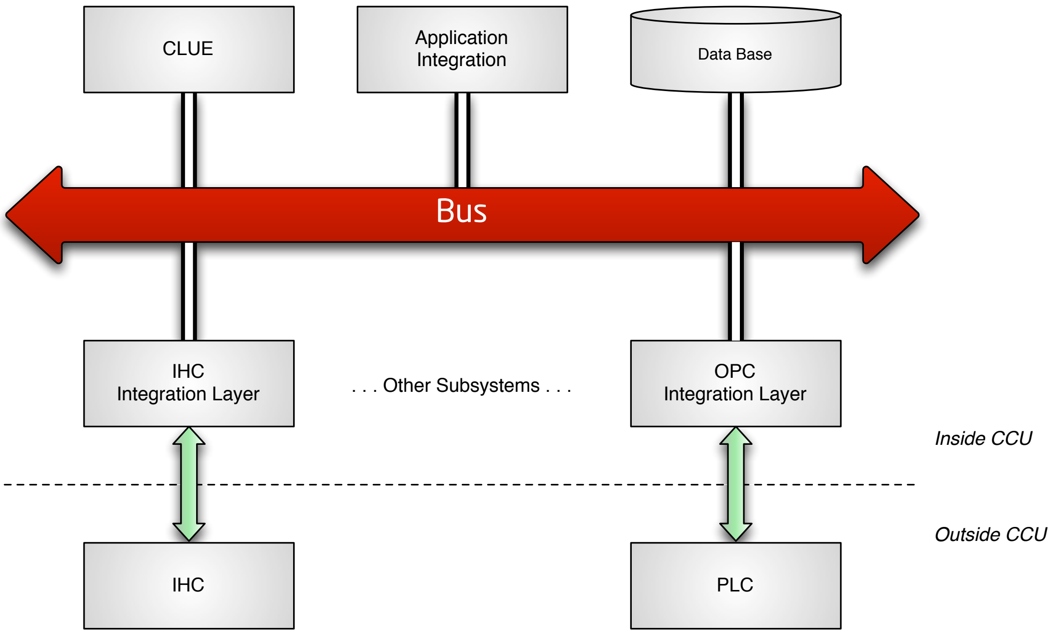
- **Data Base**
  An data base will also be attached to the bus that will be able to offer historical data and keep other important data if necessary i.e. User scenarios.

- **Application integration**
  An application integration will be able to execute methods that are based on the use cases from **Figur 8**. In this case it will be an internet based solution, namely a WebService. However, a different kind of service could also be made, that would function locally at the CCU, but if such an application is already that close to the Bus, then it might just be best to communicate directly on the bus itself.

- **Service layer on-top of each subsystem**
  To be able to access the subsystems (IHC, PLC etc.) they will need have integrated a service that follows the CCU's data exchange protocol on the bus, that will be further discussed later in the report. The Bus functions like an API to the suppliers systems and it will only be possible to exchange data if this integration has been implemented. Therefore it is important that the protocol is easy-to-use and very *generic*[16].

The different components of the CCU can placed within the bus architecture, that is shown below on **Figur 11**.

[16] E.g. if the house had two different air conditioning systems that both would need to be integrated with the CCU, then it will be optimal if they both published the same type of message. Instead of the CCU needing to identify the incoming data. That would be very complicated.




**Figur 11:** Architecture of the CCU based on the bus concept

The rest of the subsystems are connected to the IHC and OPC server and can be seen from the overview on **Figur 6**. An overview of all the different sensor and actuators available will be listed:

- **OPC server**

  Sensors:

  - Water Flow
  - Temperature in domestic hot water tank
  - Temperature (Indoor/Outdoor)
  - Humidity (Indoor/Outdoor)
  - CO2 (Indoor/Outdoor)
  - Wind
  - Rain (Boolean)
  - Power Consumption (Watt)
  - Power Generation (Watt)

  Actuators:

  - Set points for HVAC system: temperature, humidity, air flow and CO2 level
  - Valve control
  - Pump control

  - WindowMaster control

- **IHC**

  Sensors:

  - Switches
  - Motion (PIR)
  - Door lock
  - Door and Windows state (Opened/Closed)
  - Dusk sensor (Sunset/Sunrise)

  Actuators:

  - Lights
  - Power Sockets
  - Door lock
  - Alarm system

### 4.1.1 Logical Distribution

Since some of the subsystem will work autonomously, they will not publish much information as they follow their own instructions. It could then have been arguable that since little decision making is needed, that the logical decisions could be made in the integration layers. This would create less complexity for the CLUE system, since it would have less elements to take into account. The solution was not desirable, since it would create decoupling and decentralization of decision making.

The integration layers are only meant as a gateway to the CCU. They are only supposed to be forwarding data onto the bus, so the CLUE can keep track of every detail of the house. This will also create a clearer view of each components responsibility e.g. if some data has not arrived at the CLUE, but it is known to be published from the IHC, then it is clearly recognizable, that the integration layer of the IHC is not working properly. The same accounts for decision making e.g if the PLC has published a higher temperature than allowed and the message could be seen on the bus, then it is also recognizable, that the CLUE is not invoking the messages properly.

## 4.2 Invocation of message

For the system to able to invoke messages, it requires a communication channel with the bus. This is done by creating a bus listener (Called "BusWorker"), that will only invoke specified message types e.g. if the system has not been configured to invoke motion detection messages, then it will neither be used in the decision making nor be recorded by the data base.

Whenever a specific message type is picked up by the BusWorker, then it will be invoked by calling a method directly specified to handle such message types.

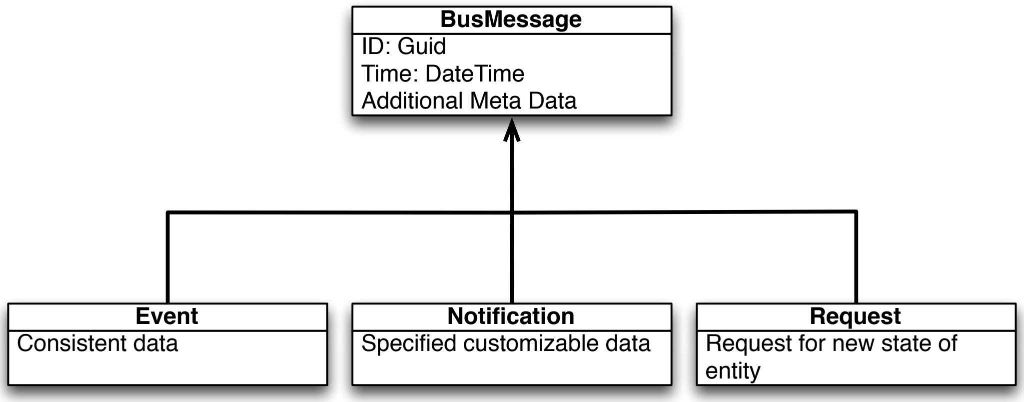
## 4.3 Messages of the bus

It is now a good time to get a better understanding of the messages (called ”BusMessage”) used on bus. They will be declared as a abstract object, that contain only the necessary meta-data to be distributed. This makes it possible to extend the BusMessage into more specific types of messages later on.

The name, that the BusMessage will be given, will function as it’s type. E.g. if the IHC will publish a message called *LightMessage*, then it is clearly known what that BusMessage contains. However, there will a naming convention for different type of messages, that each has their own purpose.

### 4.3.1 Message types

The BusMessage is the parent message and there will be three subclasses of message types:



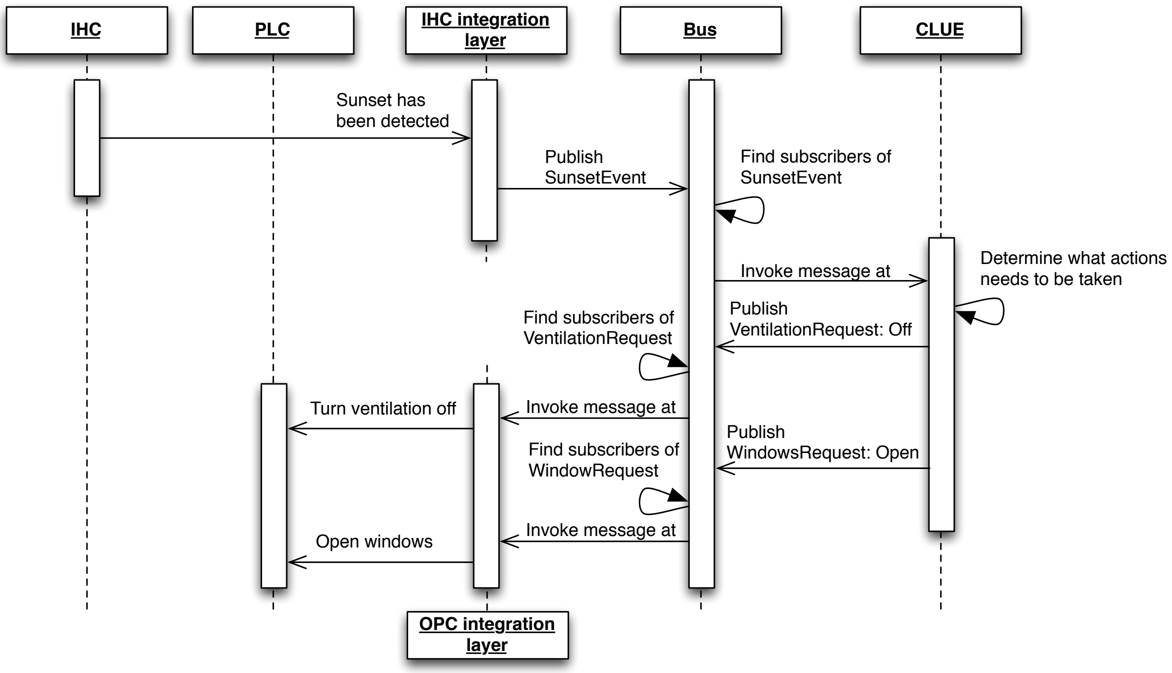

**Figur 12:** Hierarchy for BusMessages in the CCU.

- **Event**
  Events is an extended version of BusMessage and therefore already contains the fields of that, so the unique feature of events is consistent data. In this system, consistent data is regarded as data that is highly reliable and in most cases should be recorded or invoked by CCU components. An example of this could be temperature measurements, that originates from the HVAC system. Naturally, the CLUE system would invoke events to perform logical decision e.g. if the temperature stated in the event is higher than the desired, then the CCU can perform the necessary tasks to decrease the temperature of the house.
- **Request**
  A request is BusMessage that contains actions that needs to be executed by any given system in the CCU. The message could be a request to turn on a specific lamp e.g. a *LightRequest* is published by the CLUE and thereby it should be invoked by the IHC integration layer, that shortly after would publish an event announcing the state of that specific light. This can be used as a confirmation of the request to whether or not the request was successfully invoked.
- **Notification**
  Notification BusMessages is customisable data, that is only invoked by certain system in special

scenarios and are considered to be less critical in the decision making process of the CLUE. E.g. it could be power measurements, that does not need to be invoked by no other than the data base, because other systems will request this information from the data base anyway. It could also be a weather notification from the weather service, which is not so critical for all systems.

### 4.3.2 Overview of the bus

The bus is capable of publishing messages including a waiting period and setting up subscribers, so messages can be invoked. A sequence diagram will show how a sunset event could be handled:




**Figur 13:** Sequence diagram of how a sunset could be handled.

The IHC will detect the the sun has gone down and the IHC integration layer will be notified internally. A *SunsetEvent* will then be published by the IHC integration layer. The bus will invoke the event first and thereby find the subscribers of that type. The only subscriber in this case, is the CLUE and the message will then be forwarded. The CLUE's BusWorker will now invoke the message and call the responsible method. Logical decision will now be determined by the CLUE and it concludes that the mechanical ventilation can be turned of and windows can be opened instead. The CLUE will first publish a *VentilationRequest* that requires the ventilation to be turned off. The bus will then find the subscribers and forward it to the OPC server, who then will make sure that the PLC is notified. The same will happen with *WindowRequest*.

## 4.4 Sensors

It has now been presented what could happen if a sensor event has been detected and it basically functions like that for all sensor events. All sensor event will be aggregated in CCU and thereby creating a steady flow of messages. It could happen whenever a sensor detects something or at any given time interval. E.g. A message will be published onto the bus every 3 min containing the specified data.

## 4.5 Actuators

It can now be recognized that the CCU is capable of controlling every element of the house, that is noteworthy for the evaluation. To get a better understanding of how the actuators can be controlled, a description of lights will be given:

### 4.5.1 Light Control

The lights will be controlled by the IHC and it offers several options of how to change lights. The different method the IHC can use to control a light is as given:

- Turn on light
- Turn off light
- Toggle light (picks the opposite of it's current state)
- Dim light down
- Dim light up
- Set point for dimmed point
- Turn all light off

Each light in the house has been assigned a unique ID number within the CCU, that will need to be provided when requesting a light change in the CCU. The IHC uses an internally assignment of IDs to all elements, but a mapping has been created together with the CCU, so they look similar from the CCU's side.

## 4.6 Application Service

The application service (called "AppService") that is used by third party programs, has been designed as a web service[17] making it available to nearly all platforms. An interface has been created, that offers some of the current functionality. Whenever a URL has been called a specific method will be called in the web service, that will publish messages onto the bus.

For example by using the following URL, it has the capability to switch on a light:

`testserver.solardecathlon.dk/AppService/Light/SetLight?lightId={lightId}&turnOn={turnOn}`

There are some changes that needs to be made for it to function correctly:

- {`lightId`} will need to be replaced by the ID number of the given light.

[17] `http://en.wikipedia.org/wiki/Web_service`

- {`turnOn`} will need to be set to either `true` or `false` depending on if the light should be turned on or off.

By calling this URL the following method will be called:

```
public LightEvent SetLight(string lightId, bool turnOn)
    {
        var request = new LightRequest
                        {
                            Origin = "AppService",
                            ResourceId = new Guid(lightId),
                            State = ToggleState.Off,
                        };
        if (turnOn) request.State = ToggleState.On;
        return BusManager.PublishAndWait<LightEvent>(request, DefaultTimeout);
    }
```

As it can be seen the a method called `SetLight` will be invoked and the parameters from the URL will be parsed to the method. The method will then create a *LightRequest*, that afterwards will be published onto the bus. The `PublishAndWait` method is used, because of user experience reasons. It will be best, if the users get a response before doing anything else.

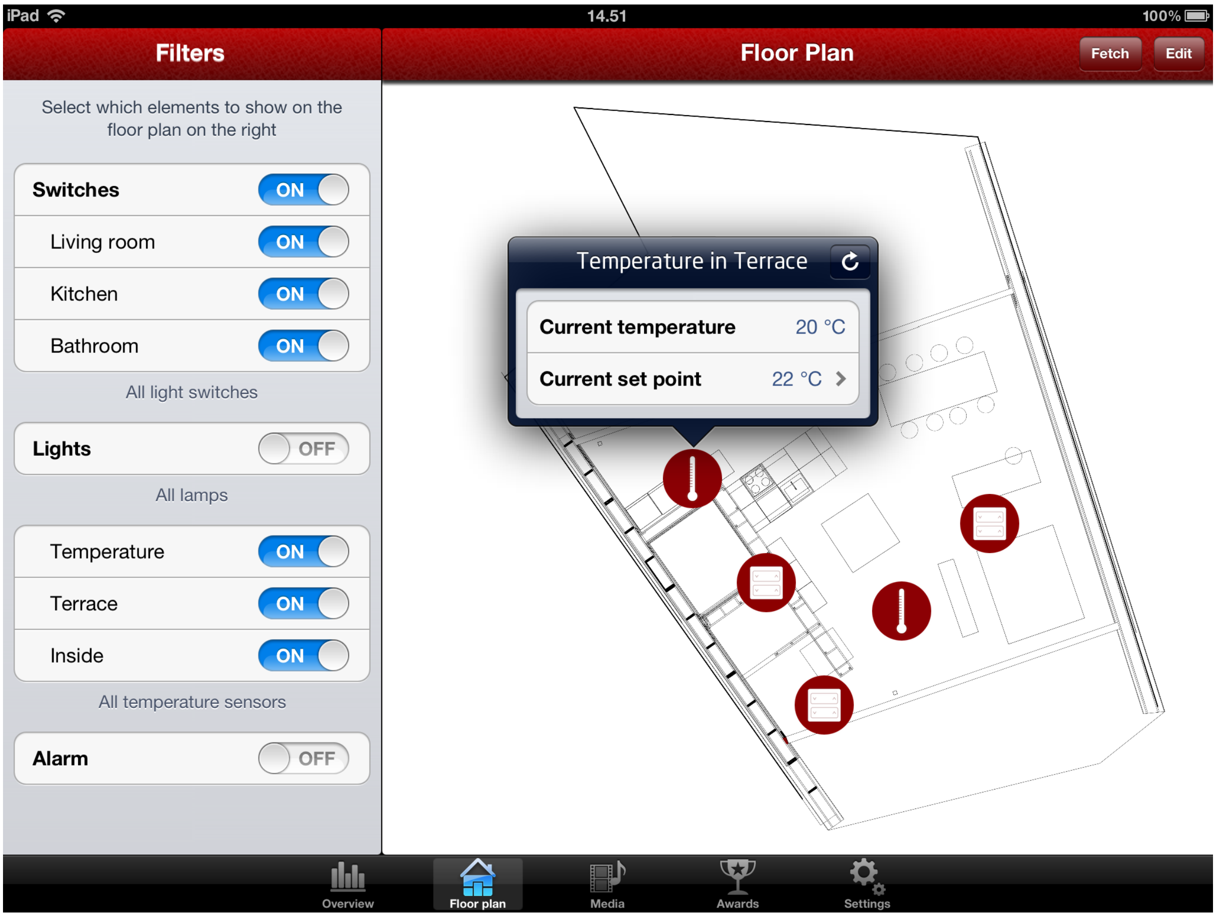
### 4.6.1 Push messages for mobile devices

The web service's push notification service is based on a third-party library that allows the CCU to send notifications to the mobile devices of the system. By simple having the token id of the mobile device, it is possible to send notifications such as suggestions. By doing so, it enables the CCU to interact much better with the inhabitants.

The current implementation supports the notifications of Apple's mobile devices, but in near future it is also possible to send push messages to Android and Windows Phone devices. The people behind the third-party library is working on a version, that supports this.

## 4.7 iPad Application

As mentioned, the CCU can be controlled by any application as long as it uses the AppService. An iPad has been created to be capable of controlling various elements of the house. The iPad App has simplified the task of handling the CCU and makes it very convenient for the users. It provides statistical information about the energy usage and it can also provide weather forecasts, that can be used to predict, if the upcoming week is going to provide a lot of solar powered energy. A screen shot can be on **Figur 14**.




**Figur 14:** A screen shot of the iPad application that has been made to control CCU.

A bonus feature, is the award system. By using Game Center, which is a system to compete with others, it is possible to get achievements in efficient energy usage e.g. if the CCU has saved 1000 watt, then it will award an achievement to them and they can brag about it to their friends. This will help improve awareness of energy usage by the users.

## 4.8 Capability of CLUE

By now, there has been numerous examples of what the CLUE is capable of. There are however some capability that has been left to be described here:

- **User location**
  The users of the system will be able to notify the CCU of their presence through an application. This information can be used to save energy, so that the house does not need have different appliances running, if the inhabitants is not home anyway. There are different notification messages, that will notify the CCU of their presence:
  - **IsHome**
    Will notify whether or not the inhabitants are current home and everything should be running according to the desired state or be turned off.

- **HomeAt**
  Will notify the system that the users will be home in a given time interval and can start doing certain tasks if necessary e.g. if it was winter, then the house could start heating up.

  Another capability that has been thought of, is tracking of the inhabitants through their mobile devices that will be running the application. This allows the application to notify the CCU without the users doing anything.

- **In-built Preferences**
  As mentioned several times, the CLUE was capable of handling different inhabitants preferences. By having certain profiles of each individual, it is possible to switch on special scenarios based on the preferences. This can be executed in the CLUE by simple making a request of enabling such a profile.

  It is possible possible to create to create this type of preference ability in the application. Since preferences is a sequence of states, it could just be implemented as a list of requests, that would be invoked by the CCU.

## 4.9 Summary

Based on the proposals that the analysis made, the design has now been shown. There has been given an overview of the different components in the current version and how each elements functions. A description of the messages and data flow has been presented and process of using the CCU through an iPad App has been shown. Finally, additionally capability of user location has been discussed. In the next chapter, there will be en evaluation of the Solar Decathlon house and it’s capabilities.

# Chapter 4

## Evaluation

An evaluation of the Solar Decathlon house will be carried out and it will be discussed which group of the extended taxonomy the house belongs to. It will clarify if the Solar Decathlon house is truly an Intelligent House and determine how successful the project has been in creating such a system for the house. The evaluation will be carried out by following the evolution model and seeing how far down the model the house will reach.

- The Solar Decathlon house fulfils the the characteristics of being a *Contemporary House*. Appliances such as lighting, ventilation, temperature of indoor air and the domestic hot water tank can all be controlled through the CCU on an iPad. The technical core consists of different components, that has been interconnected, which enables the Solar Decathlon to at least be categorized as a contemporary house.

- As mentioned, every component in the house can be controlled. This includes all the different installations of appliances; IHC, PLC, solar panels, WindowMaster, BCPM, Nilan and Uponor Unit. Not only did this allowed CCU to control every element in the house, but it also allowed the CCU to collect data from different sensors. All the components is being controlled from a centralized point, namely the CCU, that functions as the single remote controller. It is even possible to control some of the capability through motion detection, since the IHC offers such a service as one of it's sensors.

  The CCU does however not support voice nor gestures as a way to control the house, but it safe to say, that nonetheless the house is still controllable by the CCU and thereby it fulfils the requirement of being a *Controllable House*.

- Since the house has the infrastructure to become a *Controllable House*, it was also possible add programmability to the CCU. By using the solution of a bus architecture, it has become reliable to gather all the information, that is needed in a decision process. The CLUE component of the CCU is going to do all of the decision making. It enables the CCU to react to simple sensor input and also time as a parameter - as numerous examples has been explained.

  The CLUE will aggregate all of it's input and if detects a certain undesired situation is occurring and then it would perform the necessary actions to achieve the desired state of the house. This is somewhat intelligent decision making, that qualifies the house of being a Programmable house. A more precise description of the CLUE's task, would be to call it a logical decision making.

- It is possible for the Solar Decathlon house to react to certain inputs from both sensors and users, that enables the CLUE to invoke the inputs in it's logical decision process. The CCU offers a lot convenience in terms of controllability and autonomy. The CCU can prepare the house to certain scenarios and it also offers suggestions, that can be used to save energy.

The house does somewhat qualify of being a Intelligent House, but it does not fulfil the most important criteria of being able to learn. The truly Intelligent Houses has yet to be invented, but the Solar Decathlon offers a good infrastructure of being such a house. There has been no focus on creating a house that was capable of learning, so this still only qualifies the house as being a *Programmable House with a touch intelligence.*

## 4.10 Pre-Conclusion

The evaluation has shown that the house qualifies as a *Programmable House with a touch intelligence*. The characteristic in the taxonomy of being a Contemporary, Controllable and Programmable house was recognized in capability of the CCU. It offers a infrastructure that would support additional system to be added and the CLUE should easily be upgradable to a truly intelligent system, when the time comes. The house does not quite live up to the name of being intelligent, since it incorporates properties that the CCU simple does not posses.

# Chapter 5

## Conclusions

The first two chapters gives an introduction to the Solar Decathlon house and a taxonomy together with the evolution model, that was used as a tool to give an evaluation. The evolution model shows that each step down the model it goes, the houses become more advance, more powerful and grants the inhabitants more convenience in their every day life. The model is a kind of hierarchy, that has the Intelligent Houses on top, meaning they have the most potential and are the most sophisticated ones. It was was also made clear, that intelligent house is not truly available today, since they are based on technology, that is still under heavy research and development. Namely, algorithms of learning and artificial intelligence.

The next chapter gave en analysis of the Solar Decathlon project, which gave insight into the capabilities of the house. It was described how the house could control every element of the house and being able to interconnect all components in the technical core. The solution of having all components directly connected to each other, would create an incremental amount of communication channels, that was not desirable, since it added too much complexity. Using the bus architecture created a universal communication channel, that could be used by all systems by having publishers and subscribers.

To make sure that the different components would not interfere with each other, a smart CLUE system was created, that would make logical decisions based on what the current state of the house was. It was also shown how the system could be controlled by third-party applications by the help of a WebService, that was being used by an iPad App. The CLUE also offered possibility for the users to retrieve suggestions and have their own in-build preferences. The CCU system offers all of controllability as the functional requirements, but it also has achieved some non-functional requirements e.g. being extendible, simple to use, flexible and usable by suppliers, that are going to make their integration much more convenient.

Finally the designed was used to make an evaluation, that concluded which category of the taxonomy the Solar Decathlon house belongs to. It showed several characteristics of being a programmable and controllable house, but it did not present any strong evidence of being a truly intelligent house. The house was therefore catagorized as being a Programmable house with a touch of intelligence.

This thesis's goal was primarily to get a better understanding of how to build an intelligent house. It was however shown, to be a much more difficult task, than a group of students was capable of. It was managed to create a system, that would still be sophisticated and advance, yet not offer the true abilities of a intelligent house. This thesis is well read from a non-technical perspective, since it showcases many aspects of the CCU system in a easy-to-understand fashion, yet it would still be possible for an experienced programmer to implement a system such as this.

# Litteratur


[1] Molly Edmonds. How smart homes work. Website, 2008+. http://home.howstuffworks.com/smart-home.htm.

[2] Saleh Elmohamed. Examples in High Performance Fortran. Website, 1996. http://www.npac.syr.edu/projects/cpsedu/summer98summary/examples/hpf/hpf.html.

[3] Tim Kindberg George Coulouris, Jean Dollimore and Gordon Blair. *Distributed Systems Concepts and Design Fifth Edition*. Addison-Wesley, 2011.

[4] Intel. Intel home energy management. Website. http://www.intel.com/embedded/energy/homeenergy/demo/index.html.

[5] Intel. Intel home energy management video. WebSite Demo. http://www.intel.com/p/en_US/embedded/videoplayer?assetid=4268&videoid=1688462025001.

[6] Lauritz Knudsen. Lauritz knudsen intelligent house control. Website, 2012. http://www.lk.dk/lauritz+knudsen/privat/det-intelligente-hjem/lk-ihc-control.page.

[7] Boguslaw Pilich. Engineering smart houses. 2004.

[8] Marco Ryll and Svetan Ratchev. Towards a publish/subscribe control architecture for precision assembly with the data distribution service. 2007+.

[9] Mark Weiser. The computer for the 21st century. 2002.

[10] WikiPedia. Photovoltaic thermal hybrid solar collector. Website, 2012. http://en.wikipedia.org/wiki/Photovoltaic_thermal_hybrid_solar_collector.

[11] WindowMaster. Windowmaster. Website, 2012. http://www.windowmaster.dk/.