master's thesis

Demonstration case for EAGLEHAWK and IRM controllers

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Název tématu anglicky:	**Demonstration Case for EAGLEHAWK and IRM Controllers**

Pokyny pro vypracování:

V rámci diplomové práce navrhněte a realizujte kompletní demonstrační pracoviště pro zcela nový regulátor EAGLEHAWK a regulátor IRM. Prezentační pracoviště se bude skládat z demonstračního panelu obsahující regulátor EAGLEHAWK, příslušných vstupně/výstupních obvodů, regulátoru IRM určeného pro individuální prostorovou regulaci, panelu prezentujícího základní stavy naprogramované aplikace a tabletu. Hlavním cílem diplomové práce je vytvoření grafické vizualizace implementované v regulátoru EAGLEHAWK a nadřazené grafické vizualizace, která se bude nacházet na integovaném tabletu. Nadřazená grafická vizualizace bude vytvořena v programu COACH AX a implementována přímo v regulátoru EAGLEHAWK. Výsledná aplikace by měla být také vzdáleně přístupná přes internetový prohlížeč prostřednictvím bezdrátového připojení.

Seznam odborné literatury:

[1] BACnet 2011 en ; BACnet in public buildings ; Brochure No. 112 en
[2] Stephen L. Herman, Bennie L. Sparkman: Electricity and Controls for HVAC/R, 6th Edition
[3] Ross Montgomery, Robert Mcdowall: Fundamentals of HVAC control systems

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Thank you.

Declaration

I declare that I worked out the presented thesis independently and I quoted all used sources of information in accord with Methodical instructions about ethical principles for writing academic thesis.

Abstrakt

Účelem této práce je realizace demonstračního pracoviště pro dva zcela nové reuglátory a ověření jejich schopností na poli řízení moderních budov. Pro tuto demonstraci je navrhnut kufr, který je vyplněn všemi potřebnými součástmi. Dostupnost poskytuje nejen kabelové připojení, ale i WiFi instalované v kufru. První z kapitol se zabývá nejdříve návrhem kufru a poté fyzickou realizací.

Pro účel demonstrace je využito dvou vzduchotechnických jednotek, které jsou znázorněny schématicky. Obě jednotky jsou navrženy pomocí Mollierova diagramu s podmínkami, které jsou využívány pro Prahu. Simulace první z jednotek je založena na fyzickém popisu chování vzduchu v reálné vzduchotechnické jednotce a její reakci na manuálně nastavené podmínky. V případě druhé jednotky simulace ukazuje reakci na podmínky reálného okolního prostředí.

Další z částí této práce se zabývá návrhem grafického rozhraní, které slouží k ovládání celého demonstračního pracoviště, a také k prezentaci jednotlivých výsledků a dat. K tomuto návrhu je využito osvědčených principů a vědeckých poznatků o lidském vnímání.

Funkčnost celého pracoviště je v závěrečné části ověřena jak pomocí porovnání s podklady v případě grafického rozhraní, tak i zobrazením výsledků jednotlivých testů v případě simulovaných jednotek.

Výsledkem je plně funkční demonstrační pracoviště, které je možné ovládat pomocí grafického rozhraní i pomocí fyzických vstupů. Grafické rozhraní poskytuje informace nejen o výsledcích jednotlivých simulací, ale i o aktuálních průbězích. Grafické rozhraní je, stejně jako veškerá logika, nahrána v jednom z regulátoru. Díky zabudovanému bezdrátovému připojení a možnosti spustit GUI pomocí běžného webového prohlížeče je pracoviště dostupné z většiny běžných zařízení.

Klíčová slova

regulátory, vzduchotechnika, regulátory pro budovy, vzduchotechnická jednotka, fancoil jednotka, návrch vzduchotechniky, demonstrační pracoviště

Abstract

The goal of this study is to implement a demonstration workplace for the evaluation of two new controllers for their abilities to control modern building systems. For demonstration, the suitcase was designed and equipped with all necessary accessories. The network connectivity is ensured both by wired connection and WiFi.

The thesis describes the design and physical implementation of the whole workplace. For illustration, two air-handling units expressed schematically are used. Both units are designed with Mollier's diagram with conditions for Prague. The simulation of the first air-conditioning unit is based on physical description of behaviour of air inside the real unit and its reaction to manually set parameters. In case of the second unit, the simulation shows reaction to conditions set by the real environment. The functionality of whole workplace is evaluated and the results are presented.

The GUI is designed to be intuitive. The control logic has been tested and found to be working correctly. The result is a fully functional demonstration workplace which is capable to be controlled by both graphical user interface and physical inputs. The GUI provides information about both results of each simulations and actual processes. The interface is, as in case of logic, uploaded to one of the controllers. Thanks to installed wireless connection, it is possible to run the GUI via common web browser, which is available on most of the common devices.

Keywords

controllers, air-conditioning, building controllers, air-handling unit, fan-coil unit, air-condition system design, demonstration workplace

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Abbreviations

In this thesis are used following abbreviations:

HVAC	Heating, ventilation and air-conditioning plants
HMI	Human Machine Interface
H-X diagram	Mollier's diagram used for air condition unit's design
AHU	Air-handling unit
GUI	Graphical user interface
IDE	Integrated development environment
VPL	Visual programming language
HRV	Heat recovery ventilation

1 Introduction

In today's world, we are recognizing major advancements in the domain of Intelligent buildings. This technology should provide energy efficiency and comfort factor for the end users. Requirements of the users are becoming more and more demanding and hence the device needs to be improved. With technology raising and shifting its boundaries, the market has to react adequately and offer newer devices which are intended for controlling. It is a common understanding that the process of buying and selling of devices depends not only on the intelligence of the devices, price etc., but also on the manufacturer's ability to present his offer and negotiate with the user.

The main goal of this study is to create a demonstration workplace with two brand new controllers. For each of the controllers one air-handling unit is designed with Mollier's diagram. For design and creation of the whole driving strategy, default conditions for the Czech Republic is used. The controller's ability is evaluated by comparison of driving strategy with expected behaviour of units. This workplace will be used by the manufacturer, Honeywell company, to present this abilities of the controllers in real market to the customers. In many cases, the demonstration workstation will be used for presenting outside the laboratory so it's necessary to choose appropriate solutions according to transportation of the whole object.

Each of the devices are placed in a suitcase, which is the best medium for transportation and also for conducting presentations. In this way it is possible to use the workstation in every place where electricity is available, e.g. for exhibitions and presentation to customers. The whole workstation is clearly arranged into two parts, control part and presentation part.

As has been mentioned, the suitcase is separated into two parts, each part in one cover. These parts together demonstrate the functionality of two air-handling units. The first one is in the model of a general air-handling unit and the second one is in the model of a fan-coil unit both designed with same process, by Mollier's diagram. In the control part all devices determined to control the various units are placed along with connection to controllers and consumption measurement. In the presentation part are inputs, outputs, equipments like switchers, drivers and LED diodes. The whole workstation is capable to present reaction both to real environment and to simulate conditions setted by user.

This thesis is divided into several sections. The first part contains the process of design and physical realization of station. The second part consists of design of a simulation environment and its controlling based on physical processes of pressure, temperature and humidity in real environment. And the last part is determined to the design of proper user interface based on human perception.

The end result of this work is the complete design of two air-handling units, suitable graphical user interface and also verification of functionality of setted control strategy in the workplace. This station is capable to present most of the abilities in the controlling scope and also in data presentation using graphical interface.

2 Design and realization of demonstration workplace

This chapter provides information about physical realization of the demonstration workplace. As has been mentioned before, the whole workplace is incorporated into a suitcase for easier transport. Technical details about the devices used are also mentioned here.

2.1 Parts description

The whole workspace is divided into two covers of the suitcase by the sense of use. The first cover contains devices used for driving the demonstration, measuring the electric consumption and manageing the access to controllers logic. The second part is used for presentation, input data collection and for measuring the real room condition.

2.1.1 The control part

This part could be called brain of the whole workplace and ensures managing of simulation, reaction and presentation. For all these functions it is necessary to have:

- EagleHawk controller,
- IRM controller,
- panel inputs/outputs module,
- router,
- sockets - for connection to the other suitcase cover. In this demonstration workplace RJ-45 connectors are used.
- Electricity meter and A/D converter.

EagleHawk controller

EagleHawk controller is a device used for driving heating, ventilation, air-conditioning plants and seamlessly integrating other building appplications[1]. The controller has many versions, the one used here has the default option without integrated inputs/outputs and HMI. Among the basic capabilities of bus connections include BACnet®, LonWorks®, ModBus and M-Bus. Also available are the USB and Ethernet port.

This kind of controller is suited as a master to large sized building automation systems. As mentioned earlier it can not only control many HVAC systems but also help in energy consumption reduction, night air-handling, lighting, shading, heating and energy measurement and many other functions. This controller has BTL and AMEV AS-A certification and is possible to be used in both local and network systems. Local and remote user control is not only supported by a special software but also via common internet browser with proper version of Java with HTTPs communication. The controller also support multitasking, so it is possible that the control procceses depend on their priority[1].

For physical mounting, as in the case of this workplace, it is most common to use DIN rails. It is also possible to place the device into cabinets, fuse boxes and on the walls.

This controller is used in the workplace connected with the I/O module, with IRM controller and router. Every connection uses different communication protocol to show as many functions as possible. I/O module is connected via PanelBus, IRM controller via BACnet and router through Ethernet port.

PanelBus is a two-wired bus which transfers only informations. The manufacturer recommends a maximum length of $40m$[2].

BACnet Building automation and control network. Standard protocol created especially for communication between devices in building automation field[2].
This protocol defines 3 general parts:

- objects - data points, required values, schedulers, calendars
- services - data sharing, alarms and events handler, timing, network and device management
- communication media standards - via IP, Ethernet, LON, RS232.

IRM controller

IRM controller - The MERLIN. This devices is generally used for a room or small area controlling. It can be connected via BACnet and other protocols to network and configured through the special application on Android via WiFi. The application supports configuration of fan-coil unit, air quality control, underfloor heating, chilled and hot ceiling as well as radiator heating applications. All of these applications can be configured simultaneously in one device. The major advantages of this controller is that it is not necessary to have highly educated staff. For configuration, it is enough to have parameters and staff who know how to control the application.

As has been mentioned already, configuration of device is carried out through a mobile application. For configuration, it is necessary to have an Android device with the application and special WiFi module connected to the controller[3].

Physical mounting is possible on DIN rails, into cabinets, fuse boxes and on the walls. In suitcase, controller is mounted on the DIN rails. The device is connected with EagleHawk controller with BACnet protocol.

Inputs/outputs module

Panel mixed I/O module is connected to EagleHawk controller and provides data from presentation part via Panel Bus (details in section 2.1.1). It is a model having fixed terminal blocks with screws.
This module has:

- Analog inputs - 8 inputs, setted to NTC20k option with protection against failure voltage.
- Analog outputs - 8 outputs, used for LED diodes control.
- Digital inputs - 12 inputs, used for switchers.
- Digital outputs - 6 relay outputs.

Other informations are available in documentation[4].

Router

For communication via WiFi a router ZyXEL N300 is used. It is a commonly available device with 300$Mbps$ transmission speed.

Electricity meter

Electricity meter allows to measure total and partial energy consumption, current, voltage, and also real, apparent and reactive power. For connection to bus the analog/digital converter is used, which is connected to EagleHawk controller using serial port and to electricity meter via M-bus[5].

M-bus Meter bus. This standard is designed for devices determined for data collection and transportion from sensors (e.g. water flow, gas flow, elektricity). It supports maximum 250 elements on the network (possible to extend with concentrators)[2].

2.1.2 The presentation part

This section contains the description of the most important parts in the presentation cover. For better visual effects PVC plate is used as a background for all LED diodes, switchers and controllers.
The presentation part contains following elements:

- General air-handling unit scheme,
- fan-coil unit scheme,
- LCD wall module,
- tablet,
- LED diodes, switchers and controllers,
- sockets - for connection to other suitcase cover.

General air-handling unit

In these days almost every intelligent building is equipped with air-handling units. For these reasons, general air-handling unit scheme is chosen as one of the elements for presentation.

Air-handling unit is a device which is determined to control and adjust air temperature and humidity in the building. Among the others abilities, it can control air quality and air flow with the help of techniques like controlled air-handling and air circulation. This ability helps in increasing energy efficiency, therefore economy advantages. In general, air-handling can be realized naturally or using forced ventilation. In case of air-handling unit, intake of fresh air is controlled by forced ventilation, using fan[6].
The whole device contains:

- Heat-recovery unit,
- mixing chamber,
- heater,
- cooler,
- fans,
- humidifier,
- filters,
- dampers.

Refer to section 3.2 for further details.

Fan-coil unit

The label fan-coil(fan-converter) indicates that the unit contains cooler and/or heater, heat recovery unit and fans with filter. These units are used both in large buildings, e.g. hotels, administration buildings as a local area unit and also in homes. It is possible to use two versions, one is a 2-pipe version and the second one is a 4-pipe version.

Disadvantage of the 2-pipe version is that it needs to be choosen between summer and winter operations. This operation is changed using the temperature of water in the system. In case of a 4-pipe version, water for heating and cooling is divided into two systems. This thesis contains the scheme for a 4-pipe version[7].
In reality, we can see two types of mounting:

- Ceiling mounted unit.
  The biggest advantage of this type of unit is saving of space in the room. The flow of air from the unit is controlled by adjustable blinds.
- Wall mounted/standing type.
  These type of units are mounted to the walls or can be free standing in the room. Usually they are placed near windows.

Figure 1 Ceiling mounted unit[8]

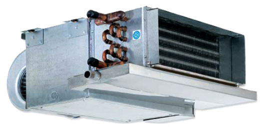

Figure 2 Wall mounted type[9]

Each part of the unit is described in section 3.3.

LCD wall module

Wall module, used in this workplace, communicates via 2-wired (polarity independent) Sylk bus with MERLIN controller. It is a simple wall module determined to control temperature and fan speed. This version also allows measuring of CO_2 concentration[10].

Sylk Bus is 2-wired, polar-independent bus which supports both power supply and information transport[2].

Other devices

Part of the workplace include, among the other devices, tablet and controlling elements. Tablet is a general 8” device with Android operating system. Tablet is used for data presentation and also for presentation of programming the MERLIN controller.

The other elements are LED diodes, which are determined to display status of the device, and switches for setting input values.

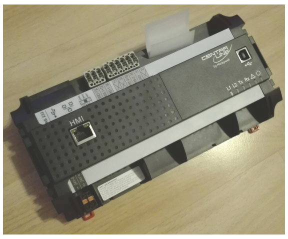

Figure 3 EagleHawk controller

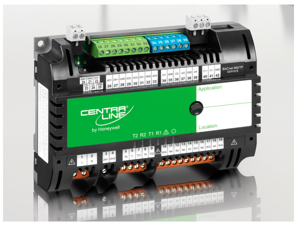

Figure 4 MERLIN controller

Figure 5 Input/Outputs module

2.2 Workplace design

Before physical realization, it is better to proceed first with design in the form of a model. The first design for this demonstration workplace is made in a 3D modeling software. 3D modeling has a lot of advantages like it shows the final design in proper measurements besides others. This design brings only general image of the final realization. Also it is possible to find out how much material is probably needed. In the end the workplace is realized in a lightly different arrangement. This is caused by changing the elements during realization.

The list of elements used for the control part is seen in section 2.1.1, and for the presentation part in section 2.1.2.

2.2.1 Control elements design

Both of the simulated units have requirements for a number of inputs and outputs. The design is also based on requirement from Honeywell company, i.e. use the outputs that are already available. Number of inputs are determined by simulation and control requirements.
The list of inputs:

- Exterior air temperature,
- exterior relative air humidity,
- interior air temperature,
- interior air relative humidity,
- required interior air temperature,
- CO_2 concentration in the room,
- room occupation.

Inside and outside temperatures are set by potentiometers, because they simulate resistance thermometers. Same elements are used for controlling inside and outside relative humidity.

Quality air controlling is also a part of work. Air quality is measured by VOC sensors or CO_2 concentration in air. On this values depend comfort, tiredness, concentration and even small health problems. Too high values may cause concentration reduction, tendency to fall asleep, headache and in extreme cases fainting. The permissible limit for air quality in rooms in Czech Republic is set as $1500 ppm$ CO_2 in air. This limit is too high, according to tests the bad effects begin around $1000 ppm$ CO_2 in air, which is hence the limit used in this work[11].

The concentration of CO_2 is controlled via switcher. The user can set only situation under/above the limit. This limit has importance in driving scope and in economy results.

The last values which affect controlling strategy is room occupation. Modern units use this information in winter time for room pre-heating. It is disadvantageous to let the room get chilled or to heat the room to high required temperature when there is nobody occupying it. For this reason it is required to set the inside temperature to $18°C$ even when the room is unoccupied[6].

2.2.2 Comparison with final realization

The following figures show comparisons between the first designs of both parts with final realization.

1. The control part

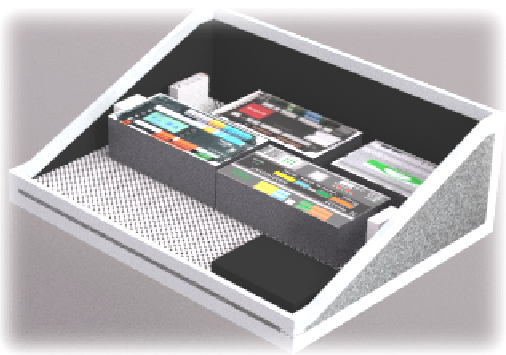

Figure 6 The first design - The control part

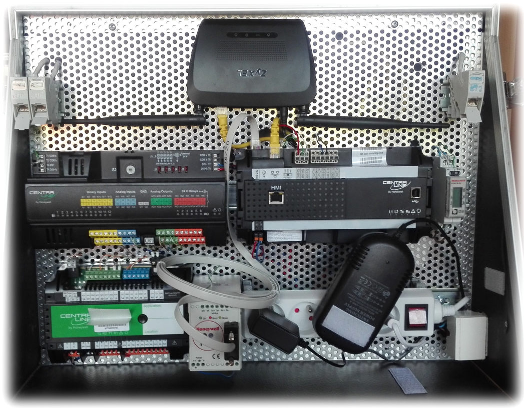

Figure 7 The final realization - The control part

2. The presentation part

Figure 8 The first design - The presentation part

Figure 9 The final realization - The presentation part

The goal of this chapter is to present the process of design demonstration workspace and physical realization. At first it is necessary to know about the number of inputs and outputs. For better idea a 3D modeling software is used. Based on the general requirements from the company for presentation application, it is very important to design as many outputs as possible to show the maximum details. The realization in suitcase allows to divide the workplace clearly into two parts, based on functionality.

In both parts are deviations in final physical realization, because equipments were changing during mounting and designing. In case of presentation part, there are deviations in design, clearer representation of both units and labels. The control part comparison shows the changes in the equipment types and also router position.

As has been mentioned before, in the control part are located both controllers, I/O module, electricity meter and A/D converter, router and sockets for power supply and connection to the other cover. The common practice is to mount most of the devices on DIN rails. The whole cover has a section of metal mesh and two DIN rails. Both the controllers, electricity meter and A/D converter, I/O module and socket are mounted on DIN rails. The router is mounted directly to the metal mesh.

The presentation part contains schemes of two air-handling units, i.e. general scheme of air-handling unit and fan-coil unit. It also contains LCD wall module and LED diodes with control elements. For better visage, the whole cover is filled with plastic plate. Whole plate is covered by printing, only space for tablet is visually separated by other color and tilt. This arrangement allows easy changes in future, because it is possible to print the other arrangement and use it instead of this one.

Diagram of whole workplace is available in appendix A.

3 Environment for simulation and air condition units

This chapter is dealing with complete design both of the simulation environment and the air condition units. As has been mentioned before, one of the unit reacts to real environment and collects input data from thermostat placed in one cover. The second one reacts on conditions laid down by the user. This unit further simulate the whole air flow and air adjustment in every part of the unit. For complete simulation it is also necessary to have an imaginary interior environment, which is also described here. This chapter also consists of description of each of the unit's elements.

In the end, there is a section on control strategy which is used for simulation.

3.1 Simulation environment

One of the major parts of the simulation is the presence of an imaginary interior environment. This space defines behaviour of incoming air from unit and its mixing with interior air. In this thesis it defines an environment which will probably be used in future for presentation of the whole demonstration workspace, i.e. a large office in an administration building.
Important details about office for proper simulation are:

- Position of object,
- maximum occupancy,
- area size,
- the minimum amount of outdoor air exchanged,
- heat losses,
- heat load of object.

Position of object affects the default design conditions. For this study the area is chosen on the outskirts of Prague. Area which is adopted for this simulation is in the ground floor of a fully glazed building facing the north-west direction.

Maximum occupancy is important for the calculation of the minimum amount of outdoor air exchanged. For design maximum count of 20 people was chosen.

Area size - according to the number of occupants it is possible to calculate minimum required area. This area is calculated based on the norm ČSN 735305 - Administration building and spaces. In case of offices which are not meant for conducting meetings but have a storage compartment, every person should have at least $8m^2$ of space.

$$S = n \cdot S_{min} = 20 \cdot 8 = 160m^2 \tag{1}$$

Where n - number of people, S_{min} - minimum space required per person.

The minimum amount of outdoor air exchanged is the value setted by hygienic requirements under the law of the Czech Republic. All of these requirements should guarantee exclusion of the health risks for human or define at least acceptable risk in areas where it is impossible to attain these standards[11].

According to the Decree No. 20/2012 Coll. about the technical requirements of the building, the minimum quantity of outsourced outdoor air should be at least $25m^3/h$ per person.
In this thesis the minimum limit value of outsourced air used is $35m^3/h$.

3.1.1 Heat losses

For every building which is supposed to be equipped with air condition unit the heat losses in space must be calculated. This information allows us to design the unit to proper values. Approximate estimate could be calculated by online tools which proved to be satisfactory in our case.
For this estimate is necessary to have:

- location - Prague,
- outdoor calculation temperature = $-15°C$,
- average outdoor temperature during heating season = $5.1°C$,
- the number of days during heating season = $254 days$,
- neighborhood of the building - object is not shielded by other,
- glazing of the object - excessive glazing of the building, over 40%,
- average indoor temperature = $22°C$,
- total heated area = $160m^2$,
- average construction height = $2m$.

With these parameters was obtained a value for heat losses equal to $Q_L = 13.5kW$.
The total value was setted by web application [12].

3.1.2 Heat gain of the building

As in the case of the heat losses for winter season, it is necessary to know the heat load of the building for summer season. The value is equal to sum of indoor and outdoor heat gain. The total value is setted by estimate application, which brings an error to calculation, but is not so important in this case of simulation.

Indoor gain consists of the lighting gain and thermal gain from human bodies.

Outdoor gain consists of the heat gain from sunlight.

Total Heat gain of the building for simulation is:

$$Q_G = Q_{GE,R} + Q_{GI,l} + Q_{GI,p} = 2.5kW + 2kW + 5kW = 11kW \tag{2}$$

Where $Q_{GE,R}$ is the heat load from sunlight, $Q_{GI,l}$ is the heat load from lighting and $Q_{GI,p}$ is the heat load from people.
The total value was setted by web application [13].

3.2 General air-handling unit

This section contains the description of the general air-handling unit (AHU) and shows the diagram of it.

The label AHU is used for the device which is determined for heating, chilling, conditioning and air circulating of the demanded space. Generally, this unit adjusts thermal and humidity state of the air and also control the air quality and flow rate. The basic function of the AHU is to take in outside air, adjust it and supply the fresh air to the building. All exhaust air is discharged, which secures an acceptable indoor air quality. Depending on the required temperature of the conditioned air, the fresh air is either heated by a recovery unit and/or heating coil, or chilled by a chilling coil. In buildings, where the hygienic requirements for air quality are in the normal level, some of the air from the rooms can be re-circulated by a mixing chamber. This function provides significant energy savings. A mixing chamber has dampers for controlling the ratio between the circulated, outside, and exhaust air[14]. Air ventilation can be designed as natural or forced. In case of the AHU, the unit is designed with forced ventilation, i.e. with the fans, so it can be controlled and also it is possible to control air flow. The following diagram is that of a unit for yearlong air temperature, humidity and quality adjustment.

The following diagram is also shown in the presentation part of the workplace.

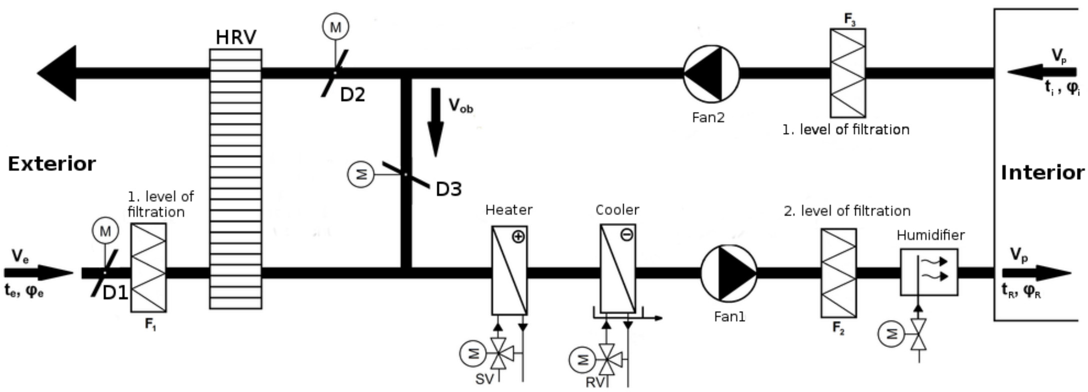

Figure 10 Scheme of general AHU[14]

In the next part, the description of each of the elements of AHU is given. This part does not contain description of filters, because these elements not allow any control features. In real situation it is only necessary to calculate the pressure loss in a circuit. This loss is not stated in this thesis.

3.2.1 Unit's elements

This part contains the functional description of individual unit elements.

Dampers

The whole unit contains three dampers as shown in the diagram. These dampers are responsible for intake and exhaust of the air and mixing fresh air with circulated air. The dampers are labelled as **D1, D2, D3**.

The damper **D1** is determined to control intake of the fresh air from outdoor to the unit. It is placed in the supply part of the unit (left side in the diagram). The level of opening of this damper depends on the air quality in the room (CO_2 concentration). As has been mentioned before, in this thesis the limit for CO_2 concentration in the air set to $1000ppm$. Functioning of the damper is further affected by temperature in the room. Using this damper it is possible to equalize heat loss or heat gain in the room.

The **D2** is a damper which is determined to control air flow during circulation. In every situation the air exhaust from room is equal to the air supply to the room so this damper is in coordination with damper **D3**.

The last one, damper **D3** reacts to air quality in the room. In cases where the CO_2 concentration exceeds the limit, this damper is closed and the unit sends only fresh air to the room. In other situations it is economically inappropriate to use a large amount of fresh air, so there is mixing with part of exhausted air from the room.

Heater

The next element in the diagram is a heater. The sign represent a water heater which serves to heat the air to required condition in winter and partly in the transitional periods. In real situations, this is basically the heat recuperation exchanger water - air with certain temperature drop. Control of the water heater is carried out using a three way valve. The controlling unit sends data with required open level to the valve, which is driven by a servo. This is the method to control the ratio between hot water from the boiler and chiller water returning from the system. This water further flows through the exchanger where it provides its energy to the flowing air. The mixing in the valve is often solved by quantitative regulation, i.e. regulation is realized by change of water volume, not by water temperature change. Qualitative regulation (change the flowing volume) would be less effective here because the efficiency of water heater is decisive of the difference in temperature between water and air.

Chiller

The main goal of this element is to decrease the air temperature. As in case of the heater, the chiller is a recuperation exchanger water-air. The difference between two of these is in their construction. The chiller needs larger area for temperature exchange and more rows of plates in exchanger than heater. This requirement arises due to smaller temperature difference between exchange medium (water) and flowing air, which is chilled. In this thesis the water chiller is simulated, where flowing water with certain temperature drop takes energy from flowing air through the plates of the exchanger. Another type of this element could be the vapor-compression type, which works on the principle of refrigerant - air. In this case liquid refrigerant is injected to the flow of air, which evaporates and takes energy from the flowing air through the walls of the exchanger.

There are two methods of chilling the air, dry and wet. The type chosen depends on the process of chilling, if condensation is there or not. In case of dry chilling the average surface temperature of the exchanger is higher than the dew point temperature of chilled air, so the humidity still remains the same during temperature reduction. The wet chilling process is completely opposite. The average surface temperature of the exchanger is lower than the dew point temperature of the air and because of this condensation of the steam occurs during chilling. It is necessary to calculate with both reduction of temperature and humidity of the air. In real situations it is also necessary calculate with volume of the condensate.

In contrast with the heater, here is a more suitable quantitative regulation, i.e. regulation is managed by changing the water volume in exchanger with constant temperature.

Fans

For air circulation and ventilation in air-handling unit, it is necessary to have fans. This element is contained in every AHU unit, for controlling the air volume. Basically it is a rotation machine equipped with blades, which serves to transport the air to a ventilated space. In practice, we use four types of fans, i.e. centrifugal, axial, diagonal and diametral. In real applications centrifugal fans are most commonly used and hence is chosen for this study too.

The centrifugal fan has a fan wheel, inlet and outlet ducts and fan housing. These fans use the kinetic energy of the impellers to increase the volume of the air stream, which moves against the resistance caused by ducts, dampers and the other components. According to the shape of the blades, we can recognize three types of centrifugal fans, i.e. forward-curved, backward-curved and straight curved. Device with forward-curved blades is cheaper, has higher efficiency ($40\% - 50\%$) and is easier to manufacture. The wheel usually has $40 - 50$ blades with constant width. This one is the general type used in air handling units. Fans with backward-curved blades have more efficiency ($40\% - 50\%$) and are manufactured with fewer number of blades ($4 - 15$)[15].

The main goal of the fan is to provide enough pressure to cover pressure loss in the whole unit, pipelines and air distribution in the room. Regulation of pressure is made by speed control. The speed is set by frequency modulation. With this type of regulation we can control fan in whole scope of $0\% - 100\%$.

In real situations it is necessary to consider fan's heating. In this simulation we can neglect this behaviour.

Heat recovery unit

Another device in the air-handling unit is the heat recovery unit. This unit uses heat from room exhausted air. It takes heat from the air and gives it to fresh air from outdoor. This unit thus helps the heater to heat the air to the required temperature. Combination of pre-heating by heat recovery unit and heating by heater increases efficiency and thus the heater can be designed to lower load.

The principle of this device is based on air-to-air heat exchange and the most common types are the recuperator and the regenerative heat exchanger.

Regenerative heat exchanger is a type of heat exchanger where heat from the hot fluid is intermittently stored in a thermal storage medium before it is transferred to the cold fluid. To accomplish this the hot fluid is brought into contact with the heat storage medium, then the fluid is displaced with the cold fluid, which absorbs the heat[16]. In practical case a wheel filled with storage medium is placed between two pipelines. In one position of the wheel is the heat accumulated to storage medium from exhaust air. After rotation to the second position the heat is transferred to fresh air. The main disadvantage of this type is that for rotation it is necessary to have electricity. This disadvantages is compensated with high efficiency. The load of this type of exchanger is possible to be controlled by changing the rotation speed. Among the other advantages, exchanger transfer sensible and latent heat and has lower pressure loss.

Recuperator is a type of exchanger where the heat transfer is carried out directly through a panel of exchanger. For this type it is not necessary to have wheel with storage medium, therefore no need for electricity. Its disadvantages include lack of fluent regulation (only ON/OFF), higher pressure loss and lower efficiency. Recuperators transfer only sensible heat and is necessary to place filters in both exhaust and inlet pipeline[15].

It this study the system is designed with recuperator type of heat recovery unit.

Humidifier

The last device in the scheme is the humidifier. There are several types of humidifiers, i.e. drums, disc wheels, bypass flow-through and spray mist.

Very often used is the bypass flow-through type. In real situations this type is probably the most suitable for air-handling units. The air is moistened with water steam, which is produced from heating element inside the unit. The steam is mixed with air in a special chamber and chilled to optimal temperature[17]. From hygiene point of view this is the ideal solution because all bacteria and other microorganisms are killed during boiling. The disadvantage is that this type consumes more electricity than others. This disadvantage is not completely true, because other types need after-heating due to temperature decline after moistening.

This type is also used in design in case of the AHU.

3.3 Fan-coil unit

The fan-coil unit (FCU) is a unit which works with constant air flow. This unit is equipped with fans, filters, heat exchanger, heater and/or chiller. This unit adjust air from the room to required conditions and returns it to the indoor space. In case of bad condition of the indoor space, more volume of fresh air is supplied than the minimum requirement. There is no specialized unit for humidity adjustment. This adjustment is realized as a result of air behaviour during heating and chilling.
In this thesis the following scheme is used:

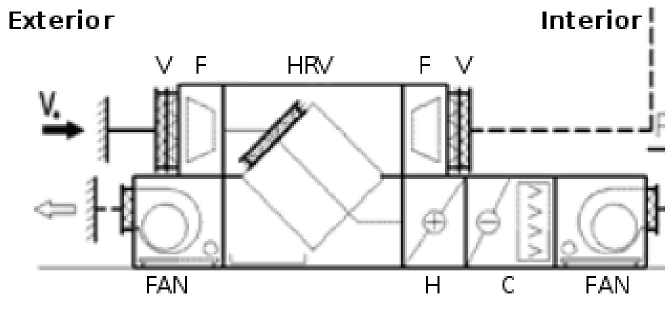

Figure 11 Scheme of FCU[18]

The whole unit consist of:
- Fans **FAN**,
- filers **F**,
- heater **H**,
- chiller **C**,
- heat recovery ventilator **HRV**,

- valves **V**.

The description of each of elements is mentioned in section 3.2.1.

3.4 Default conditions for design and control

For every design of air condition units it is necessary to know the input values for calculation. Important values in this case are air temperature and humidity. These values is further used in the H-X diagrams for calculation parameters of the units. In table 1 both winter and summer interior and exterior parameters are shown. According to the location and purpose of the building, the parameters are shown for the office building in Prague.

Exterior air parameters	summer	$t_e = 32°C$	$h_e = 58\frac{kJ}{kg}$
	winter	$t_e = t_{e,calc} - 3°C$	$\varphi = 100\%$
		$t_{e,calc} = -12°C$ for Prague	
Interior air parameters	summer	$t_e = 25°C$	$\varphi = 50\%$
	winter	$t_e = 22°C$	$\varphi = 30\%$

Table 1 Table of default design conditions

3.5 Design AHU parameters

This section deals with the design of both the AHU and the FCU. For proper design it is necessary to have several input parameters.
The parameters are:

- Heat losses - section 3.1.1
- Heat gain - section 3.1.2
- General design parameters for specific area - section 3.4
- Occupancy

With these variables it is possible to design parameters for both units. There are several possibilities to design it. Here the Mollier H-X diagram is used.

The Mollier Diagram (H-X digram) is the European version of the Anglo-American Psychrometric Chart. They are identical in content but not in appearance. This diagram is based on the relationship between enthalpy and water vapor content of air. The heat or energy content is difficult to measure directly, so the diagram is cunningly distorted to give the illusion of being based on the relationship between temperature and relative humidity and water vapor content. Temperature and relative humidity are easy to measure and so the diagram is transformed into a useful tool[19]. Basically, this chart allows the designer to view approximate state of the air in the specific location in the unit. The descriptions of using the diagram is mentioned in both case of design.

3.5.1 Specific designs

Every unit is designed for two limit conditions, i.e. winter and summer season. This process makes sure that every requirements are covered for all unit's elements.

Summer season

The first design is focused on the summer season. In this season compensation for heat gain in the room is expected. So for this part consider major value of heat gain, occupancy and general design parameters for summer season in exterior and interior 3.4.

Outside air volume $V_{OA}\,[m^3/h]$
Requirement for fresh air is calculated using the hygienic limit and occupancy of the room. As has been mentioned before, the hygienic limit is set to $35m^3/h$.

$$V_{OA} = D \cdot n = 35 \cdot 20 = 700m^3/h \tag{3}$$

Where D - Volume of fresh air in m^3/h and n - occupancy.

Supply air volume $V_{SA}\,[m^3/h]$

$$V_{SA} = \frac{Q_G}{\rho \cdot c \cdot \Delta t_p} = \frac{11k}{1.2 \cdot 1010 \cdot 6} = 5443m^3/h \tag{4}$$

Where Q_G is the heat gain of the building $[W]$, Δt_p is the temperature difference $[K]$, c is the specific heat of air $[J/kgK]$ and ρ is the air density $[kg/m^3]$.

Recirculated air $V_{CA}\,[m^3/h]$
The total volume V_{SA} of the supplied air consists of fresh air V_{OA} and circulation air V_{CA}. The mixing of these two parts of total volume is done in the mixing chamber. Hence it is easy to calculate the circulated air using the following equation.

$$V_{CA} = V_{SA} - V_{OA} = 5445 - 700 = 4745m^3/h \tag{5}$$

Air temperature after mixing $t_{MIX}\,[°C]$
The last value which is necessary to have is air temperature after mixing circulated air and fresh air. This value is calculated using weighted average with volume impact.

$$t_{MIX} = \frac{V_{OA} \cdot t_e + V_{CA} \cdot t_i}{V_{SA}} = \frac{0.194 \cdot 32 + 1.32 \cdot 25}{1.51} = 25.96°C \tag{6}$$

Where $t_{e/i}$ are the temperatures of exterior/interior $[°C]$ and all volumes are in $[m^3/s]$.

Construction of H-X diagram -
with all of these parameters it is possible to construct the Mollier Diagram. The complete construction of the diagram allows to calculate the load of the chiller.
Process of diagram construction:

1. Exterier point **E** - design parameters for exterior,
2. interier point **I** - design parameters for interior,
3. between these two points is a mixing point **MIX** with appropriate temperature t_{MIX},
4. average temperature of chiller surface **CH** - $9°C$,
5. the last point **R** is the point which has parameters to the required supplied air state. It is constructed via point **CH** and **MIX**. For calculation a PC software is used so the position of the point **R** is more accurate[20]. In case of hand construction the point is placed on the line between the points **MIX** and **CH**.

After that it is necessary to read all needed values for chiller load calculation.
The diagram is on picture 12, full scale diagram is given in appendices A.

Chiller load $Q_{CH}\,[W]$
For calculation of the chiller load it is necessary to know enthalpy after mixing state (point **MIX**) and requirement state (point **R**). The chiller load is not possible to be calculated using temperatures as in case of the heater load, because in this case both the absolute humidity and temperature are changed.
Chiller load is calculated using the following equation:

$$Q_{CH} = V_{SA} \cdot \rho \cdot (h_m - h_r) = 1.51 \cdot 1.2 \cdot (51.8 - 43.1) \doteq 16kW \tag{7}$$

Where V_{SA} is necessary to calculate in $[m^3/s]$.

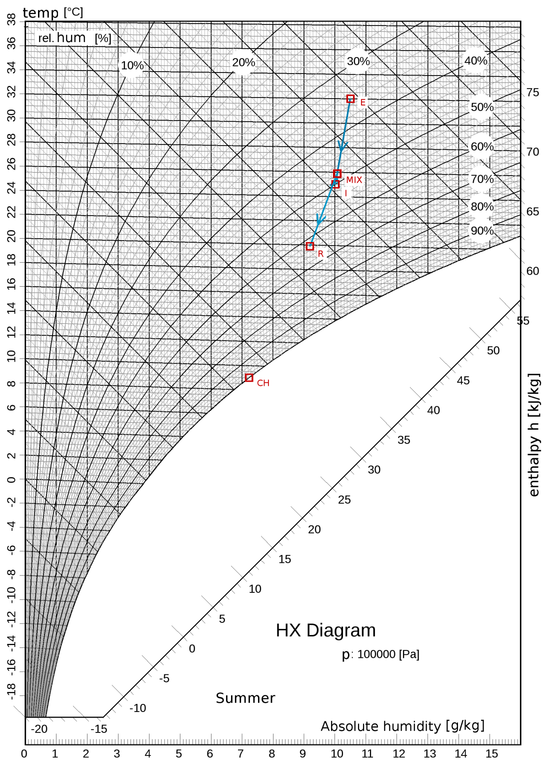

Figure 12 The Diagram for summer season

Winter season

In the winter season is necessary to calculate parameters for heater and humidifier to secure comfort in the room. Basis for calculation are again default design conditions (section 3.4). In this part of the year the heater and also the heat recovery ventilator works in coordination. This unit is dimensioned to maximal air volume and help the heater with air pre-heating. The process of unit design for winter season is based on same knowledge as in the case of the summer season.

Temperature difference in winter season $\Delta t_{SA}\,[°C]$
In winter season it is necessary to supply air with higher temperature than required temperature in the room because of the heat loss of the building. This difference is calculated using the following equation.

$$\Delta t_{SA} = \frac{Q_L}{V_{SA} \cdot \rho \cdot c} = \frac{13.5k}{1.51 \cdot 1.2 \cdot 1010} = 7.4°C \tag{8}$$

Where Q_L is the heat loss $[W]$, V_{SA} is the supply air flow $[m^3/s]$, ρ is the air density $[kg/m^3]$ and c is the specific heat of air $[J/kgK]$.
This difference allows to calculate the temperature of supplied air.

$$t_{SA} = t_i +_\Delta t_{SA} = 22 + 7.4 \doteq 30°C \tag{9}$$

Where t_i is the interior temperature $[°C]$.

Air temperature after Heat recovery ventilator $t_{HRV}\,[°C]$
This unit is used in winter season for air pre-heating. Hence it is not necessary to dimension the heater to extremely high load. In this thesis regenerative heat recovery is used, so it means it is transferring only sensible heat. For all HRV units the main property is the heat transfer coefficient Φ. This number shows the efficiency of the heat exchanger and in this study it is set to $\Phi = 0.8$. With all these parameters it is possible to calculate the temperature after heat recovery exchanger.

$$t_{HRV} = t_e - \Phi(t_e + t_i) = -15 - 0.8(-15 + 22) = 14.6°C \tag{10}$$

Air temperature after mixing chamber $t_{MIX}\,[°C]$
For calculation of the air temperature state after mixing, indoor temperature and temperature after HRV are used. For calculation it is necessary to use weighted arithmetic mean, because of different air volumes.

$$t_{MIX} = \frac{V_{OA} \cdot t_e + V_{CA} \cdot t_i}{V_{SA}} = \frac{0.194 \cdot 14.6 + 1.32 \cdot 22}{1.51} = 21.2°C \tag{11}$$

Construction of H-X diagram - with all these parameters it is possible to construct the whole H-X Diagram. The complete construction of the diagram allows to calculate the load of the heater and the humidifier.
Process of diagram construction:

1. At first point **E** is placed, which has default design parameters for winter-exterior. With the same procedure it is possible to place point **I** with winter-interior parameters.
2. The first change of the air state is made by the HRV unit. Thanks to the chosen unit type (transferring only sensible heat) the only necessary parameter is the air temperature after heat recovery ventilator t_{HRV}, so it's possible to place point **HRV**
3. After that, air is flowing through mixing chamber, so the next state is defined with temperature t_{MIX} and is placed on the link between points **HRV** and **I** - point **MIX**.
4. Next unit in air flow is the heater. This unit doesn't affect the air humidity so with knowledge of temperature after heating t_{SA} it is possible to place point **H**.
5. The heated air requires only the right value of humidity at this stage. As has been chosen before, in this thesis bypass flow-through type is used, which add only humidity and temperature stays the same. With this knowledge it is possible to place point **R** as a required state of supplied air.

After this it is necessary to read all needed values for heater and humidifier load calculation. The diagram is on the picture 13, full scale diagram is possible to find in the appendices A.

Heater load $Q_H\,[W]$

The heater load is calculated with temperature after mixing and for supplied air (points **MIX** and **H**. This load is possible to be calculated with temperatures because in case of heating there is no transfer of latent heat, only sensible heat.

$$Q_H \;=\; V_{SA} \cdot \rho \cdot c \cdot (t_{SA} - t_{MIX}) \;=\; 1.51 \cdot 1.2 \cdot (30 - 22.1) \doteq 17kW \tag{12}$$

Where V_{SA} is necessary to calculate in $[m^3/s]$.

Humidifier load $Q_{HM}\,[W]$

The humidifier load is possible to calculate with enthalpy difference of points **R** and **H** with further equation.

$$Q_{HM} \;=\; V_{SA} \cdot \rho \cdot (h_R - h_H) \;=\; 1.51 \cdot 1.2 \cdot (43 - 41.5) \doteq 3kW \tag{13}$$

Where V_{SA} is necessary to calculate in $[m^3/s]$.

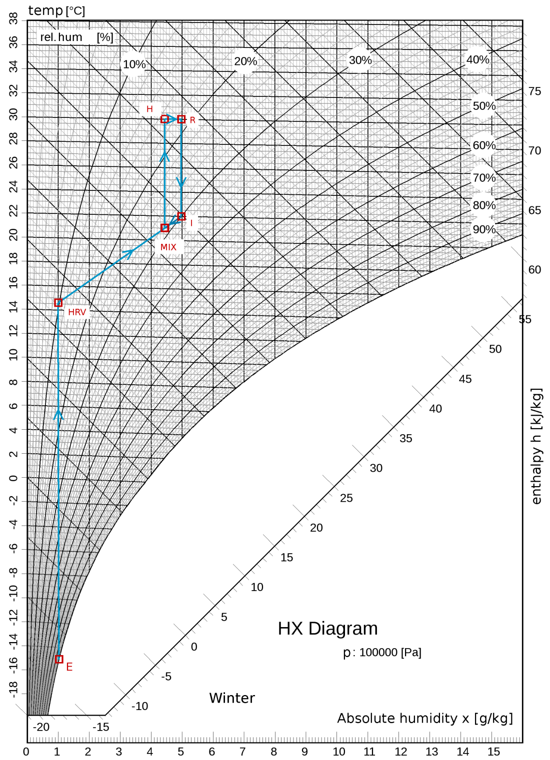

Figure 13 The Diagram for winter season

3.6 Design FCU parameters

The designing of fan-coil unit has the same rules as in the case of AHU in section 3.5. The only one difference between these two procedures is that the designer has to realize the FCU unit, doesn't have the humidifier unit. So in the end of the unit there is no humidity adjustment. In fact it is not affecting the final state in the interior, because in most cases the air will be moistened by humans body. In the end, the occupancy will ensure suitable parameters in interior.

All loads are chosen same as in the case of AHU.

3.7 Simulation model AHU

For simulation of real air flow in AHU it is necessary to calculate actual state of air after every element of the unit. For this calculation the following equations are used. The actual state of the air is determined by its temperature, enthalpy and absolute (or relative) humidity. For finding the actual state it is enough to have two of those parameters[21].

Water vapor saturation pressure $p_{ws}\,[Pa]$

Water tends to evaporate or vaporize by projecting molecules into the space above its surface. If the space is confined the partial pressure exerted by the molecules increases until the rate at which molecules re-enter the liquid is equal to the rate at which they leave. At this equilibrium condition the vapor pressure is the saturation pressure[22]. This pressure depends only on actual air temperature. For more accuracy it is necessary to distinguish two temperature intervals.

- For interval $< -20; 0°C)$

$$p_{ws} = exp(28.557 - \frac{5951.3588}{268.78 + t})\ [Pa] \tag{14}$$

  Where t is air temperature.

- For interval $< 0; 80°C >$

$$p_{vs} = exp(23.58 - \frac{4044.6}{235.628 + t})\ [Pa] \tag{15}$$

  Where t is air temperature[21].

Water vapor partial pressure $p_w\,[Pa]$

We can use relative humidity as the ratio of vapor partial pressure in the air - to the saturation vapor partial pressure if the air is at the actual dry bulb temperature[22]. Water vapor partial pressure is possible to get from one of the following equations or we can use these equations to get other parameters as the relative humidity.

$$\varphi = \frac{p_w}{p_{ws}} \rightarrow p_w = \varphi \cdot p_{ws} \tag{16}$$

$$p_w = p \cdot \frac{x}{0.622 + x} \tag{17}$$

Where p is the atmospheric pressure a x is the absolute humidity of the air[21].

Absolute humidity of the air x

Absolute humidity is the total mass of water vapor present in a $1kg$ of air. It does not take temperature into consideration[22].

$$x = 0.622 \cdot \frac{p_w}{p - p_w} \tag{18}$$

Enthalpy of moist air $h\,[kJ/kg]$

Moist air is a mixture of dry air and water vapor. The enthalpy of moist and humid air include:

- the enthalpy of the dry air - the sensible heat,
- the enthalpy of the evaporated water in the air - the latent heat.

The total enthalpy - sensible and latent - is used when calculating chilling and heating process.

Specific enthalpy h of the moist air is defined as the total enthalpy of the dry air and the water vapor mixture - per unit mass of dry air[22].

The equation is:

$$h = c_{pa} \cdot t + x \cdot +(h_{we} + c_{pw} \cdot t) \tag{19}$$

Assuming constant pressure conditions: $c_{pa} = 1.01 kJ/kgK$ is the specific heat of air at constant pressure, $c_{pw} = 1.86 kJ/kgK$ is the specific heat of water vapor at constant pressure and $h_{we} = 2500 kJ/kg$ is the evaporation heat[21].

So, now the elements are chosen, parameters are set and both AHU and FCU are designed. The next step is design control strategy, the behaviour of the units.

Summarize of parameters:

	Winter season		Summer season	
t_e	-15	$°C$	32	$°C$
φ_e	100	%	33.4	%
t_i	22	$°C$	25	$°C$
φ_i	30	%	50	%
Q_L	13.5	kW		
Q_G			11	kW
V_{SA}	5443	m^3/h	5443	m^3/h
V_{OA}	700	m^3/h	700	m^3/h
Q_{CH}			16	kW
Q_H	17	kW		
Q_{HM}	3	kW		

Table 2 The parameters summarize

4 Control strategy

With knowledge of all parameters of the environment, unit parameters and air adjustment behaviour inside the unit it is possible to design the control strategy for each part of the units. The strategy for the AHU is used only in case of this simulation, but is very similar to strategies used in real operation. The strategy for FCU is completely same as in real operation and it is ready to use.

4.1 Input and output parameters

In the beginning it is good to realize all input and output parameters for control strategy. In real situation these parameters are collected using sensors. In this study several values are collected from controllers and others from real sensors.
This strategy use these input parameters:

- Exterior air temperature t_e,
- relative humidity of outdoor air φ_e,
- interior air temperature t_i,
- relative humidity of indoor air φ_i,
- required interior temperature $t_{i,r}$,
- required interior relative humidity $\varphi_{i,r}$,
- CO_2 concentration in the room - above/over the limit,
- occupancy of the room - occupied/unoccupied,
- scheduler.

As a output parameters the user get:

- heater, chiller and humidifier load,
- air flow volume in each part of the pipeline
- alarm list
- electricity consumption of the whole workplace
- actual temperature and relative humidity state in the interior

4.1.1 Required indoor air temperature

Special attention is necessary to be given for required air temperature for interior $t_{i,r}$. This temperature is affected not only by user intervention but it also depends on room occupancy. In case when the user knows the room is not or will not be occupied in the near future, is not convenient turn off the unit completely. In this case it is better to set the temperature to maintaining value. With this function heating in the case of occupied room is faster and more economically convenient. This function is available only during winter season. In case of summer season required temperature is set to $26°C$.

For this reasons in case the switcher is in position *Unoccupied* the required interior temperature is set to the following values:

- $t_e \ < \ 18°C \Rightarrow t_{i,r} = 18°C$
- $18°C \ < \ t_e \ < \ 18°C \Rightarrow t_{i,r} = t_e$
- $t_e \ > \ 26°C \Rightarrow t_{i,r} = 26°C$

4.2 Control strategy for AHU

This part is dealing with the description of the control strategy for general air-handling unit with all the elements described above.

As has been mentioned before, the control strategy does not take into account the filters. These elements affects only pressure loss in the pipeline and it is necessary to know in case of the fans dimensioning, which is not part of this text.

Each of the elements has its own operating conditions. The control of the elements is managed by a combination of graphical user interface (GUI) and controllers placed in the covers. The function of the whole simulation is **undermined** by *ON/OFF* button in GUI. The process is divided into two states, during the unit is off it is possible to the set initial conditions in the interior, t_i and φ_i. This values is not possible to be adjusted during simulation.

In the further sections functions of all elements are described.

4.2.1 Dampers

Dampers are responsible for the supply of fresh air and also for mixing fresh and circulated air.

The dampers **D1** and **D3** have the same value for control. The main value for these two elements is CO_2 concentration limit.
In most of the days it is economically disadvantageous to supply the room only with the fresh air, so only hygienic minimum of fresh air is taken from exterior during the substantial part of the year. This air is then mixed with circulated air from the interior. In case of situation with exceeding the limit, the damper **D1** is fully opened and supply the interior with whole required air volume. The damper **D3** is closed in this situation.

The last one, damper **D2** is responsible for air extraction to the exterior. With the knowledge that the total air volume is equal to air volume required to compensate the heat gain in the room and also to sum of circulation and fresh air is obvious that this damper has to have same behaviour as the damper **D1**.

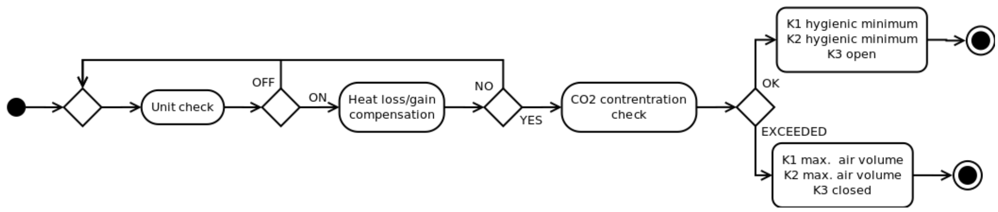

Figure 14 Activity diagram of the dampers

4.2.2 Heat recovery ventilator

The next element in the unit is the heat recovery ventilator. This unit is responsible for removing the energy from extracted air from the interior and transfer it to the fresh air from exterior. As has been mentioned before, this type of HRV transfers sensible heat so in real situation will be necessary to add bypass to the unit and also the bypass controlling. Otherwise in summer the HRV will provide the heat from interior to the fresh air.

The regulation of the HRV is depending on the heater activity. In simple words, if the heater is working then the HRV is working and otherwise, the HRV is turned off in case of non-activity of the heater. The HRV is *ON* even when it is using circulation air as the major part of the new air for the interior.

The major advantages of this unit is cheap operation, low pressure loss and high efficiency.

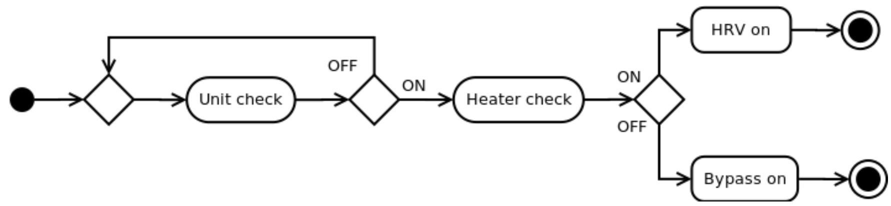

Figure 15 Activity diagram of the HRV

4.2.3 Heater

For heating activation is obviously necessary to have the interior temperature t_i lower than the required temperature $t_{i,r}$ so there is requirement to compensate the heat loss. This strategy is based on the knowledge that the space is in the administration building, so required temperature $t_{i,r}$ will be set around $22°C$.

In case of the heater are resolved two states, according to state of CO_2 concentration in the room. If there is a requirement to bring fresh air to the area (CO_2 concentration is over limit), the heater is controlling the interior temperature t_i till the exterior temperature t_e is lower than $18°C$. In this case it is more comfortable for the people to bring unheated fresh air and reduce the interior temperature t_i. Obviously, when exterior temperature t_e is higher than the interior t_i, there will be no action from the heater.

The second situation is when it is not necessary to bring large amount of fresh air so it uses only the hygienic minimum. In this situation a more accurate controlling strategy is set. The heater is activated also when exterior temperature t_e is over $18°C$. But, the limit is only made higher to $22°C$, otherwise it is inefficient to heat.

In the end the most important part of strategy is the controller setting, because in case of inappropriate setting there could be simultaneously action of heater and cooler and that is not economically efficient.

The heater is driven by PID controller which can also be used in reality 4.2.7. The advantage of this type of regulation is that it removes regulatory deviations, which is the main disadvantage of P regulation. In reality it is also possible to meet with PI regulation.

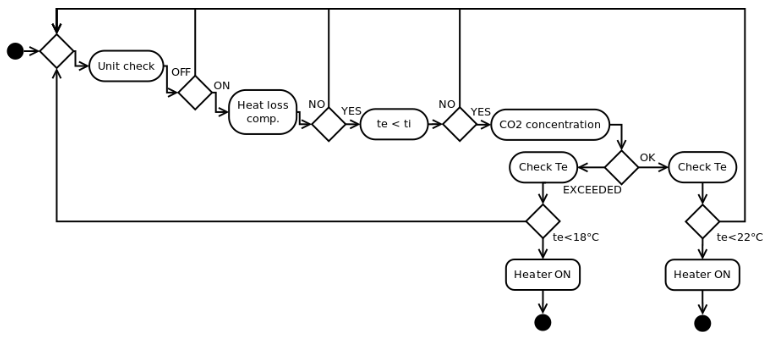

Figure 16 Activity diagram of the heater

4.2.4 Chiller

In case of chilling it is also necessary to pass a few conditions to activation. In the first case it is obviously necessary to have requirement to take the heat gain from the room, so the interior temperature t_i is higher than the required interior temperature $t_{i,r}$. Also as in case of the heater there is a condition which considers exterior temperature t_e.

The chiller is activated only if the exterior temperature t_e is higher than $t_{i,r} + 2°C$. Otherwise it is more efficient to use only free chilling with air-handling without the chiller.

For chiller usually one of the P, PI, or PID regulators are used. In this thesis the PI regulation 4.2.7 is used.

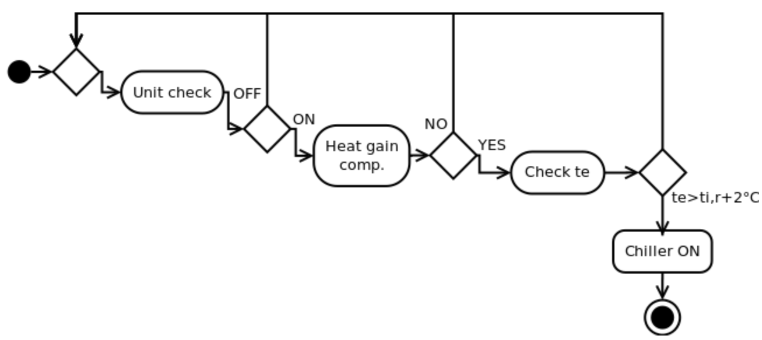

Figure 17 Activity diagram of the chiller

4.2.5 Humidifier

The other element in the unit is the humidifier. This unit is driven by P regulation 4.2.7. The usage of the humidifier is usually only in winter season, because of heating process. Heating significantly reduces air humidity as is possible to see in winter H-X diagram (picture 13).

The activation of humidifier is driven by the interior relative humidity φ_i state. In case that this value is lower than required $\varphi_{i,r}$ the unit is activated.

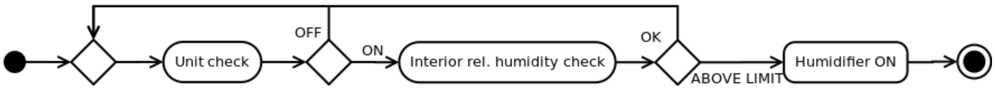

Figure 18 Activity diagram of the humidifier

4.2.6 Fans

The last units in the AHU are the fans. Activation of these unit depends on requirement to compensate heat loss or heat gain in the room and on requirement to bring fresh air in case of the occupied room. In every case when it is necessary to bring supplied air to the room, it is necessary to activate both fans.

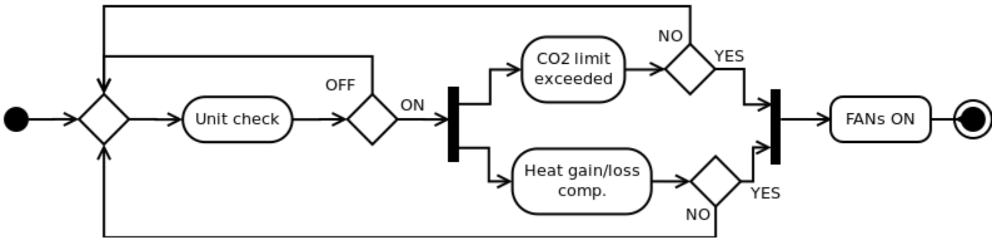

Figure 19 Activity diagram of the fans

All these strategy will be evaluated in the chapter 7.

4.2.7 P,PI, PID controllers

For better understanding, the theory of the controllers which are used for driving the components are also mentioned here. In this study three basic controller types and their combination are used, i.e. the proportional P, the integral I and the derivative D.

Basically, the controllers are trying to keep the controlled variable (in our case temperature and humidity) on a required value called set point. A feedback control system aim to this by looking at the error signal, which is the difference between where the controlled variable is, and where it should be. Based upon the error signal, the controller decides the magnitude of the signal to the actuator (element of the unit)[23].

Proportional control

In case of the proportional control, the actuator applies a correction that is proportional to the amount of error. The disadvantage of this type of control is that it can have steady-state error.

$$u(t) = k_P \cdot e(t) + u_b \tag{20}$$

Where u is an action value, k_P is a proportional constant - gain, e is an error value and u_b is a reset, bias[24].

Proportional-integral control

PI control is a combination of proportional and integral controllers. The major advantages of this control is in ability to reduce the steady-state error to zero.

$$u(t) \;=\; k_P e(t) + k_I \int_{t_0}^{t} e(\tau) d\tau \tag{21}$$

Where k_I is an integral constant[24].

Proportional-integral-derivative control

The last version combines previous control and add the last partition - the derivative control. This part is usually not necessary to use, is used only in more complex occasion or in case of higher claims. The *PI* systems reduce steady-state error but increases overshoot. Derivative control increases stability by reducing the tendency to overshoot. In this thesis it is used for the heater controlling. For heating is not necessary to use this way of control, in reality is common to use only the proportional control but is appropriate to design as possibilities as is possible.
The equation is:

$$u(t) \;=\; k_P e(t) + k_I \int_{t_0}^{t} e(\tau) d\tau + k_D \dot{e}(t) \tag{22}$$

Where k_D is a derivative constant[24].
The total functionality is mentioned in further picture 20.

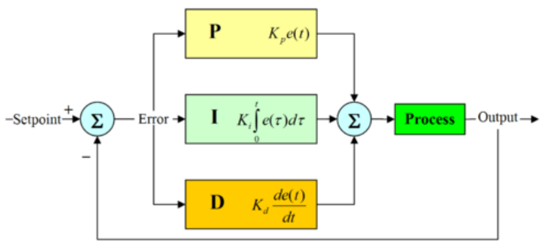

Figure 20 PID control scheme[23]

4.3 Control strategy for FCU

The control strategy for the FCU is far more simpler than for the AHU. This unit are mentioned to be placed only for the zones or the rooms, so the driving is not so difficult. The whole unit reacts only to inside temperature t_i[18]. The FCU units are not able to directly adjust humidity. So for the heating activation is necessary to keep t_i lower than $t_{i,r}$. Similar for the chilling, t_i has to be higher than $t_{i,r}$.

5 Graphical environment

This chapter deals with the description and designing of the graphical environment. In the first part details of the used language, integrated development environment and structure of the whole application are described. For proper design of the graphical dashboard it is necessary to have some basic knowledge of the principles of design, which are mentioned in the following section. And in the end the complete graphical dashboard is presented and described using modules.

Then all this logic is uploaded into the EAGLEHAWK controller, which also allows control of the other element's variables.

5.1 Programming

According to the label, this section describes programming base for creating the final application. The whole application is created in *COACH AX* IDE, which is specialized IDE from Honeywell company based on JAVA. Since the application is based on JAVA it could be used for design application structure and make it easier to understand the behaviour of the software.

5.1.1 Language

For the creation of application graphical programming is used. But, for better structure design and for understanding it is good to know that whole IDE and elements are written in JAVA.

Java

Java is an object-oriented, platform independent programming language. Also it is a high level and robust language. The advantage of the Java application is that it can be used as a desktop, web and mobile application. One of the disadvantages are its memory requirement so its not so suitable for embedded systems. But its possible to use it even there.
For this study it is good to understand the principles of object-oriented language and they are:

- Inheritance
- Encapsulation
- Polymorphism

Inheritance is when one class acquires all the properties and behaviours of a parent class i.e. known as inheritance. It provides code re-usability. It is used to achieve runtime polymorphism[25].

Encapsulation is binding (or wrapping) code and data together into a single unit. With this attitude are hidden internal details of objects so ohter participant can't see implementation of object's behaviour[25].

Polymorphism is when one task is performed in different ways[25].

Visual programming language

The process of creating the application is using visual programming language. The VPL allows the programmer to build an application via moving element with a particular function. This attitude is convenient for visually impaired people[26].

Basically, the application contains the elements with function and connections between these elements. For some people the VPL can provide an approach that is more intuitive and less cumbersome. Also many of the "graphical languages" provide online debugging, so the creator can see immediately the result of his/her action.

One of the disadvantages of the VPL is that you often cannot see what is inside the elements. The programmer is reliant to the documentation from the manufacturer. In a better case, the IDE allows the programmer to view the source of each element to better understand a function and maybe do adjustments.

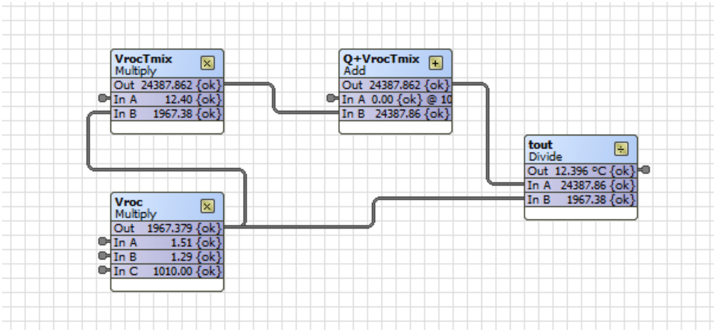

Figure 21 Illustration - the calculation of temperature after heating

5.1.2 Integrated development environment

As has been mentioned before, for programming the IDE used is *COACH AX*. This software is obviously not freeware and it has to be licensed.

The *COACH AX* is a "one-tool" solution for engineering and managing most of the Honeywell products. This IDE allows to build an application using the VPL for creating the control logic and also graphical interface. Hence it enables remote engineering opportunities of the complete system via internet using a web browser[27].

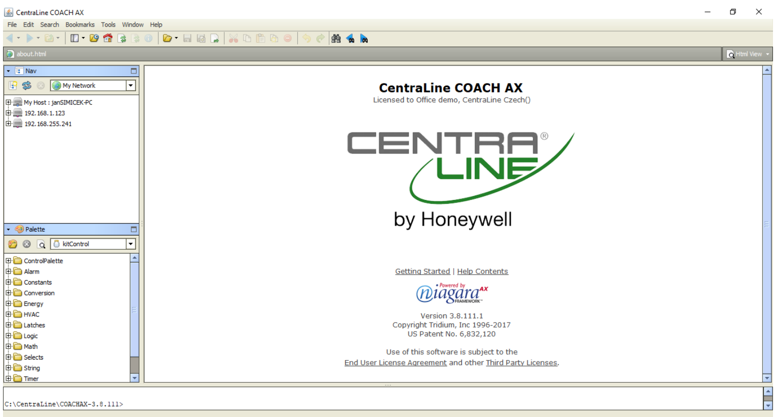

Figure 22 The Coach AX

5.1.3 Structure

In this part of the thesis the structure of the whole application is mentioned. The IDE *COACH AX* use tree structure as the way to represent hierarchy of the application. Individual parts are separated into files etc. Each of the objects contains wire sheet where it is possible to make programming via graphical representation of functions. And also every general function contains setting, where it is possible to set variable's units, other parameters and also add several extensions. The depth of structure depends on the programmer, but is suitable to separate object according to rules of object-oriented programming for the best possible transparency and also for updating in the future. Major parts of the structure are Logic, Graphics and Interfaces.

The connections between objects is possible via connecting links, so every variable, which should be visible to other structures, is available to be used everywhere in the application.

Logic

The logic part contains control strategy of whole application and calculation necessary to simulate processes inside the air-handling unit. Every element represents one file in file structure and its further divided according to its own abilities.

Another part contains constants for calculations, which are suitably separated for easier updating.

Due to this separation it is easy to find required properties and parameters during simulation for every element of the AHU.

Interface

The interface is one of the most important parts of the structure. Without this every change and checking the output value of one part becomes very difficult and time consuming. This structure is separated into three parts, where the crossing between every part is represented with one file which acts as an interface.
The parts are:

- Logic
- Graphics
- Inputs/Outputs

Logic - Inputs/Outputs interface allows the programmer to check the variables which are meant to control presentation elements (LED diodes) in the workplace and also the variables coming from workplace.

The *COACH AX* use its own interface for communication with other elements inside suitcase, i.e. MERLIN controller, I/O Module, electricity meter and router. It's called the *Drivers* (picture 23) and allows proper connection between individual units in the workplace and its setting. The major property of connection is the knowledge of BUS, which is used for connection. After connecting to other unit it is possible to change its setting, e.g. port setting in case of I/O Module.

So basically there are two interfaces, one created by creator of IDE and one created additionally. The reason for the second interface is folder integrity with the rest of logic, because the *Drivers* interface is separated in the structure and is too difficult for collecting the variables value.

Inputs/Outputs - Logic is the second, added interface between logic and external elements. Basically, it provides an environment where it is possible to check and also set properties of individual variables, especially in case of inputs.

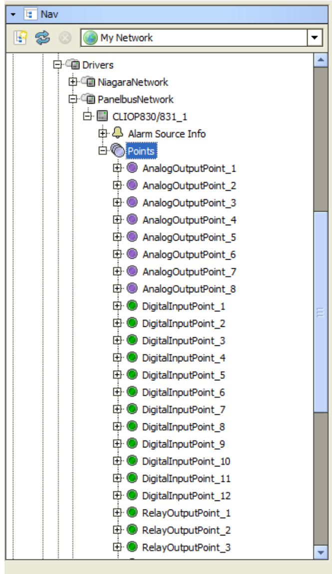

Figure 23 The drivers

Logic - Graphics is the last interface and as is mentioned above, it is the interface between the logic part and the graphics part. This is the easiest way to manage all the output variables and mainly their settings. In case of the variables, which are supposed to be presented in graphical user interface it is suitable to set its unit and other parameters.

From the description a legacy from Java is evident. At first, every object allows to set their parameters, as a unit of output variable, timing, behaviour, but this properties are, at the first sight, covered in front of the rest of the world, therefore definition of encapsulation. Also the objects can be extended by the extensions to improve its abilities, e.g. the alarm extension for alarm checking or history for collecting the values. This object is going to have more parameters and properties than the default one, therefore inheritance. The presentation of the polymorphism is also there because it is possible to use the same object which will adapt according to the incoming object type.

The tree structure of the whole application:

- **exteriorValues** - Exterior temperature and humidity
- **HRV** - Logic of HRV
  - **temp** - temperature calculation
  - **hum** - humidity calculation
  - **ent** - enthalpy calculation
- **mixing** - calculation of air state after mixing
  - **temp** - temperature calculation
  - **hum** - humidity calculation
  - **ent** - enthalpy calculation
- **heater** - heater state
  - **temp** - temperature after heating
  - **hum** - humidity after heating
  - **ent** - enthalpy after heating
  - **control** - login of heater control
- **chiller** - chiller state
  - **temp** - temperature after chilling
  - **hum** - humidity after chilling
  - **ent** - enthalpy after chilling

```
│  └─ control - login of chiller control
│ humidifier - humidifier state
│  ├─ temp - temperature after moistening
│  ├─ hum - humidity after moistening
│  ├─ ent - enthalpy after moistening
│  └─ control - login of humidifier control
├─ interior - Calculation of interior temperature and humidity
├─ Graphics_ Control - contains logic for graphics elements in GUI like
│  unit on off, occupation, fan, dampers, HRV, CO2, InterfaceAHU,
│  InterfaceInputs, Language
├─ Graphics_ Control_ Merlin - contains logic for graphics
│  elements depending on IRC controller
├─ Graphics_ Control_ ElectricityM - contains logic for graphics
│  elements depending on electricity meter
├─ requiredValues - the section dealing with required values for
│  interior
├─ scheduler - The logic of scheduler
├─ constants - all constants in one section for better transparency and
│  adjustment
└─ ChartBase - logic of charts in GUI
```

The control of all elements and their behaviour is described in the following chapter 6.

5.2 Design principles for GUI

As has been mentioned before, one of the major parts of this study is the presentation of the processes and data. This section describes several rules and tips to design the user interface. There are many ways to design proper GUI and this depends on the final product and scope of the presentation. This knowledge is collected from several resources mainly from articles [28] and [29].

5.2.1 Design principles

Every GUI should follow some general principles. There are several verified principles, which is good to follow during the design. In case of user dashboard, it is important to keep in mind that less information could be more helpful than screen overflow with informations. This section contains several tips collected from articles, obviously every situation is different so the designer has to think about every assignment separately.

- **Simple interface** - every interface should be as simple as possible. The designer often wants to have very clever interface displaying all the informations. In this case it can happen that UI is unclear, difficult to read and in the end useless. It is necessary to keep in mind that the final user need to be well-aware of all the information and analysis can't take much time.
  For example it is impossible to ask the user to do some calculation on his own. The designer needs to know for whom the dashboard is being designed. After communication with final user it has to be clear which values and what states should be displayed. Also don't underestimate the power of charts and colors.
- **Consistency** - is the next principle. The dashboard shouldn't be created from

many different types of elements. Also each of the parts should contain same type of elements. Users have more comfort and are able to better adapt if the dashboard is created in the same way. The whole UI should still be consistent, such that the user will be able to use his skills in every part and he will not be confused by different control for different sections.
In design also it is good to use common UI elements. It gives a chance to the user to use his skills and it is not necessary to learn something new.

- **Power of colors and texture** - can always help to display informations more properly than simple text. The dashboard should not be full of different colours but should have only few colours. The power of colours can also be used in case of user warning and notices. It is better to sort the colours also according to elements types, when it could be helpful with orientation in the dashboard and in charts.
  The other part is texture, when with small adjustment of the information the designer can change their meaning. For example with size, contrast, type etc.
  The tip about colors is based on traffic light. For most people the red means "bad/stop" and the green means "good/go". This is very helpful for example in case of alarms and others.
- **Page hierarchy and data distribution** - is another very useful principle. Its impossible, in case of large sized dashboards, to display all information in one page. The designer should keep in mind the distribution of information according to their meaning and also for whom the informations are obtained.
  At first it is good to realize the information distribution and design the distribution of the whole presentation application. After that it is possible to spent time for designing the layout of every page.
  The multiple pages project are used only in case of large dashboards or for example in case when there are more people with different focus.
  Also the one-page dashboard should be separated into parts according to meaning and information.
- **Layout** is based on good orientation in the dashboard. Every element must be placed into dashboard and, obviously, it is very important to keep in mind the layout of whole dashboard. The elements should not be placed randomly on page.
  The simply rule is to display the most important information first, on the top of the window. Also here it is good to know for whom the dashboard is being oriented, for example in the Czech Republic best place is the upper left corner, because that is the point where we begin reading.
- **Data context** is a section which coordinate also with colors and textures. Every data with meaning should provide theire meaning in the easiest way as is possible. For example comparison of the actual value with some limit could provide alarm situation for the user simply with color.
  In this category the legends of the charts etc. are also contained. It is good to provide maximum information, even if some of them are obvious, but the users might find them helpful.
- **Use of dashboard** says about devices and screens where dashboard will be used. At present it is possible to use a large scope of devices, the design should be aimed on to a particular one.
  For example dashboard for large screens will be designed in a particular way and contains more information in one page than dashboard for mobile phone.
  In case of general dashboard when the usage is not clear, it is important to try more screens during designing for function verification.

The basis is to create a dashboard where the user is oriented, has every information presented according to his needs. Simply, the dashboard that can be understood by the user as quickly as possible.

5.2.2 Dashboard for intelligent building - pre-attentive variables

Another method to design a proper dashboard is using directly knowledge from the intelligent building scope. Also the previous design principles are valid here. This section mentions more details about the principles mentioned above.

The knowledge in this section is taken from [30].

The most important thing about dashboard is visual design. This words are not only about nice charts and textures but also about knowledge of human reactions and behaviour. It involves how human beings perceive and act upon visual information, a science in the realm of "human factors" and "cognitive psychology".

It all starts with something known as " pre-attentive variables ", these are the attributes of the dashboard that humans subconsciously pay attention to before they consciously know they are paying attention, thus pre-attentive attributes. It is possible to use these knowledge in case of designing the dashboard for quickly displayed information, because the dashboard has user's attention before they know they're paying attention.

Informations position

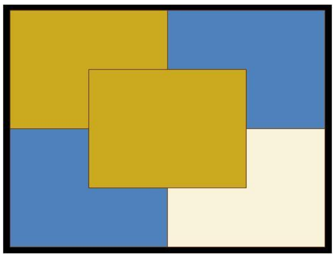

Figure 24 The positions distribution

The emphasis of the information depends on their position. The parts of the dashboard with the most emphasis are in the upper left corner (depends on the culture) and also in the center - gold rectangular on the picture 24. The next lower level of emphasis are the upper right corner (also depends on culture) and lower left corners - blue ones. The last one has the lowest level of emphasis and there should be displayed only non-important details or nothing.

So the most important data and also the warnings etc. should be displayed in the center or upper left corner of dashboard.

Color

Another pre-attentive variable is color. The colors variability has a huge importance in case of the data picking speed. The example is shown on the picture 25, where it is possible to see that squares based on blue color are very easy to pick due to color divergence.

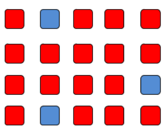

Figure 25 The colors distribution

Shapes and sizes

The last variables in this enumeration are the shapes and sizes. As in the previous case, these also help user and accelerate user reaction. Via shapes and sizes it is easy to present the sizes of value or for example the level of importance.

The final dashboard should quickly provide the values and informations to the user and allow him to react based on them. Pre-attentive variables are one of the many things which should be used in case of designing proper graphical user interface.

5.3 Graphical user interface

This part describes the actual user dashboard which is programmed inside one of the controllers. As has been mentioned before, all applications are designed in the *COACH AX* application. In this section two dashboards are mentioned according to the progress of the study.

The first dashboard was used as a service dashboard in the beginning of this demonstration workplace. After evaluating the functionality of the logic another dashboard with advanced graphical function was designed.

5.3.1 Modules

First of all, the description of modules is carried out for GUI design. In the *COACH AX* are modules also used for programming the logic.

Every company has their own graphical modules and in this study only the general ones are used. Obviously it is possible to buy more modules from specialized companies, even it is possible to order module made to measure or write one by own.

Graphical elements and its behaviour depends on the module abilities. For capable presentation it is obviously better to use the elements with animation because the people react faster to animation impulse rather than to the number representation. The number should also be provided to the user, but as the second element for refining the information.

In this study both type of modules are used - animated and without animation. This kind of attitude break the uniform assumption but the use is separated into more screens so there should not be any confusion to the user.

5.3.2 Service dashboard

First of all the service dashboard was designed for defining the calculation logic. This dashboard is not determined for final users and it should serve only to service company. For comparison with final design the service dashboard is shown in the following image 26. This service dashboard provide basic information about all elements during simulation and in combination with charts from each of the elements, it is very easy to find error or mistake in calculation. The whole dashboard was able to control both GUI and control elements in the demonstration workplace.

As it can be seen the graphics is very simple and is useless for proper demonstration to user. Besides the other reasons, the whole dashboard is designed in the Czech language, so it can not be the final version.

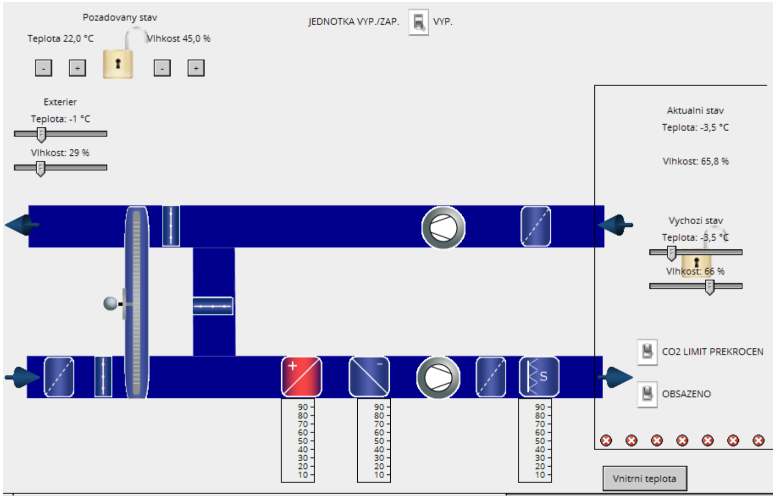

Figure 26 The service dashboard for simulation

5.3.3 User dashboard

The final version - user dashboard. The whole graphical user interface is composed from more screens:

- Dashboard - home screen with general information,
- units - graphical interface with detailed informations,
- charts - page with temperatures, humidities and loads progress during simulation,
- alarms - the detailed list of alarms caused during simulation,
- scheduler - page providing setting for scheduler.

This section deals with the graphical description of the individual pages. The control and usage is described in the following chapter 6.

Dashboard page

This is the homepage of the whole application. On this page general informations from both controllers are displayed and it provides some basic setting for simulation. Also it is capable to display the process of simulation with limited details.

The whole page is separated into individual areas via colored shapes.

The final state of the dashboard page shown in the picture below (picture 30).

The top bar is at the top of the page and is determined to switching between homepage and units page with detailed information. This buttons are located in the left sides, in the area with the most emphasis of the user.

The whole unit is translated into two languages - Czech and English. For switching between languages it is possible to use two buttons with the national flags, which are also located in the main bar, in the right corner.

In this bar we can clearly see the use of pictures instead of text for labels on the buttons. For example in the case of languages it is clear on the first sign what this buttons provide also because it is common practice to use the flags instead of text labels.

The rest of the page contains the area with default information and the other areas for the AHU unit setting and simulation and for the FCU unit and displaying their details of process.

The general informations is the first on the page in case of the whole left side and displays the details about process inside simulation, the details from the thermostat and information from the electricity meter.
In the top is located chart with inside temperature and relative humidity so the user can see in first moment what was the last progress in case of these two simulated variables.

The next one are located the information from the thermostat provides details about actual temperature in real room and CO_2 concentration. The part of this mini area is also animated element provides immediately notice about limit exceeded in the shape of light bar.

The last informations in this section are from the electricity meter provides the actual values of the current and voltage via bar graph and the other total values.

The air-handling unit informations are located as the first area on the right side. As is possible to see on the picture 30, this section is not located only on the right side but is located from the center to right so also in the other area with high emphasis to user perception. This area is determined to provide basic setting for simulation, e.g. winter/summer design and default interior conditions and general information about air flow in the unit. It is also possible to display activity of individual elements using animated graphical elements. The air flow is indicated via arrows. The other elements, e.g. heater, chiller and humidifier have their own indicator as is seen below.

Figure 27 Indication - The heater activation

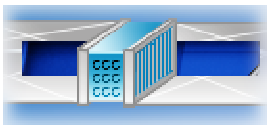

Figure 28 Indication - The chiller activation

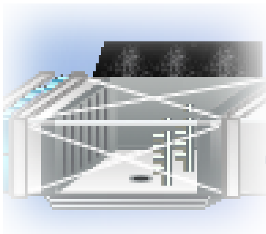

Figure 29 Indication - The humidifier activation

The fan-coil unit informations is the last section in the homepage. It is located in the area with the lowest emphasis to user - lower right corner. This location has its reasons, because this unit does not allow any settings and it has only information character. As in case of the AHU unit the activity of air flow is indicated via arrows. The other elements and their activity is also indicated in the same way as in case of the AHU unit.

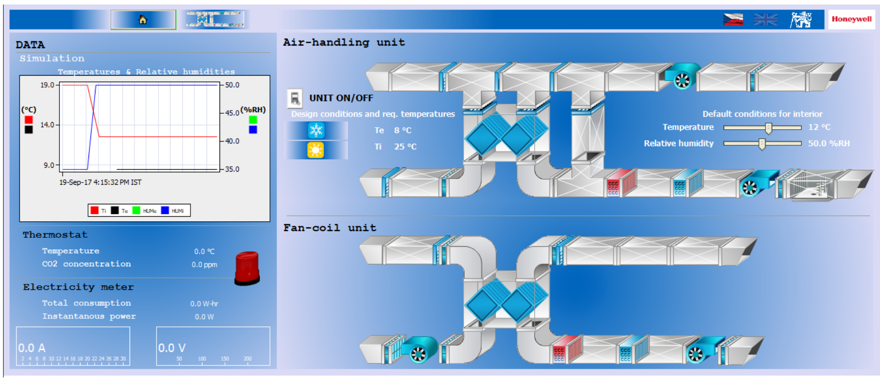

Figure 30 The Dashboard - homepage

Units page

Another page, which the user can use to gain the detailed information about the simulation progress, the FCU unit and also all data which the whole application provides, is the Units page.

Each of the units have their own tab in tab pane which is possible to switch in the left upper corner.

This pane contains three tabs:

- the EagleHawk controller - simulation details.
- The IRC controller - reaction to real environment.
- The Data page which contains all informations from simulation, IRC controller and also from the electricity meter and the thermostat.

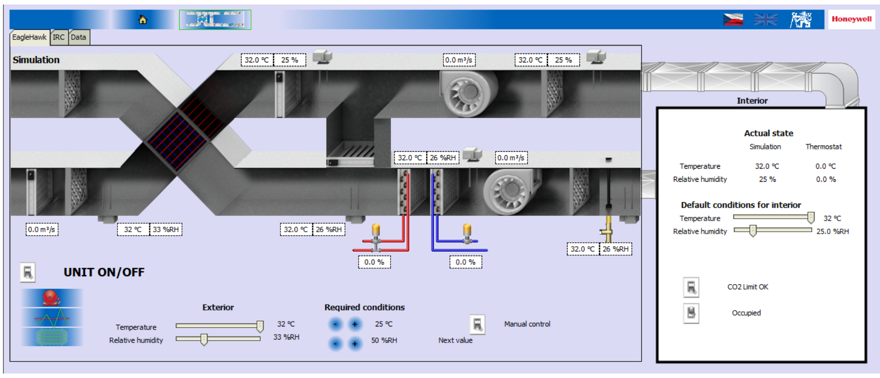

Figure 31 The default units tab - The EagleHawk simulation tab

The EagleHawk tab provides animation of the whole simulation process in the AHU unit with all possible details from inside the unit. This page also allows the user to set the default setting for:

- exterior,
- interior,
- required values,
- occupation,
- state of CO_2 concentration limit.

The layout of the page is the similar to the visualization in the real workplace, so in the left side is exterior, followed by the unit and in the right side is shown interior with its conditions and actual state. Among the others, this page allows the user to switch to charts, alarms and scheduler page. The visualization is shown in the picture 31.

The IRC tab contains the visualization of processes inside fan-coil unit. This unit is driven by logic inside IRC controller which is designed by manufacturer. In this study only reaction to conditions measured by thermometer is shown. In the left side is located the unit with individual elements and details about measured CO_2 concentration and reaction to this value. In the right side is again located visualization of interior with all necessary values from thermometer. This tab also shows the user different graphical interfaces which is possible to be designed with default modules.

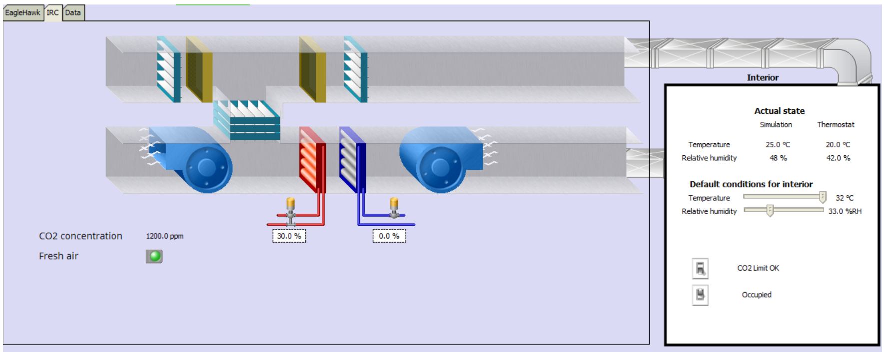

Figure 32 The IRC unit tab - reaction to real environment

The Data tab is the last tab on this page. It shows summary of all available data from both units in one table. There are also data from thermostat and from the electricity meter.

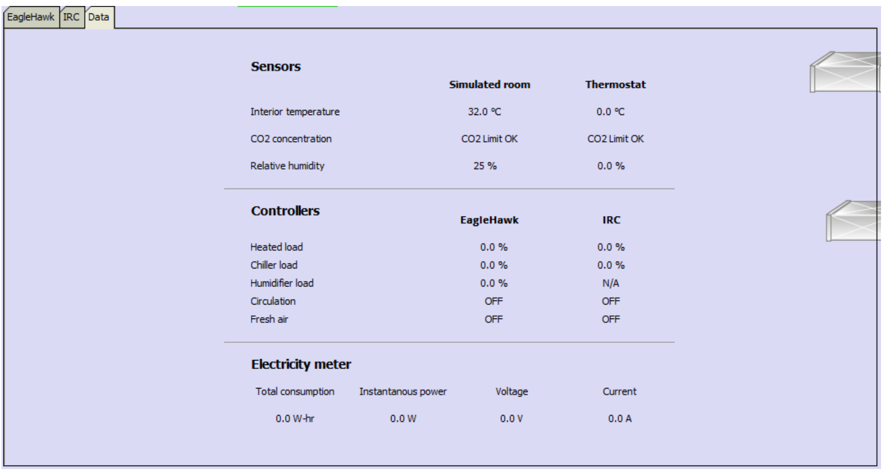

Figure 33 The Data tab

The charts page

This page is determined to show the user the process of the interior and exterior temperatures and relative humidities. Also, after switching the tab, it is possible to see the loads of the heater, chiller and humidifier.

On the left side the buttons determined to switching between pages are located and in the bottom, as the additional information, the required values for inside temperature and relative humidity are located.

The visualization is shown in the picture 34.

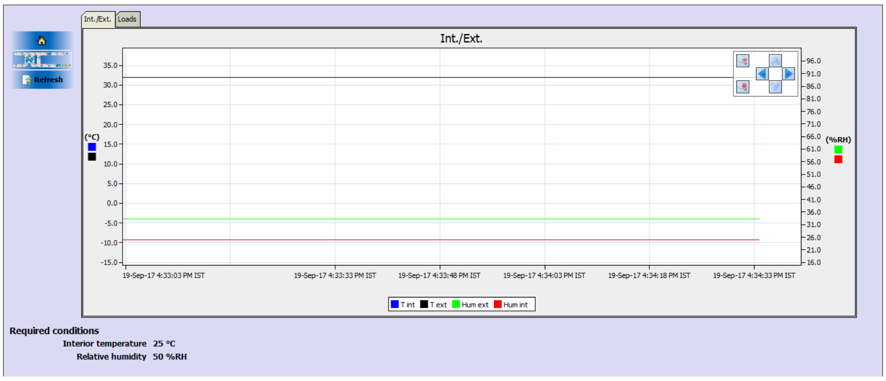

Figure 34 The charts page

Alarms page

The content of this page is composed of informations about alarms which are set by the programmer and also alarms which are checked by the application itself, e.g. periphery connection etc. The design is not part of this study because it is provided directly from *COACH AX* application.

Scheduler page

The last page of this dashboard is the scheduler page. As the label says, this page is determined to setting the scheduled action for simulations, when this input is activated by user. As in case of the alarms page, this page is also provided by the application, so the design is not part of this study.

All these pages are designed with uniform design for better transparency, only in case of units different graphical elements are used for presentation.

6 Controlling the demonstration workplace

This chapter contains the guide to control the GUI and the whole workplace. In individual sections the possibilities which the work provides are mentioned.

6.1 The GUI guide

As has been mentioned before, this section deals with description of how to use the GUI which is provided to the user. For better transparency this section is divided into parts according to GUI page with its own control.

6.1.1 The homepage

The design of the homepage is seen in the picture 30. In case of functions, this page provides:

- the setting of the default condition for simulation,
- the buttons to:
  - the units page,
  - refresh homepage,
  - the charts page.

The general information section

In this section it is possible to perform two actions - switch to the charts page and also show the alarms page.

The charts page is obtained by clicking on that area of the chart. This chart does not allow the zooming to progress, but it switches directly to the determined page.

The alarm page can be displayed by clicking on the area of light horn next to CO_2 concentration in the thermostat area.

The AHU section

This part of the page provides, among the others, general settings of default conditions for simulation via buttons with summer or winter sign. After clicking on these buttons both the exterior temperature and relative humidity and the required values for interior are set to values according to the default conditions for design and control listed in the table 1.

After pushing both buttons are disabled because of uploading the values to the simulation. Both buttons are hidden in case of ongoing simulation also. Other elements with similar behaviour are controllers of the interior temperature and relative humidity located in the right side of the unit.

The other functions, which are possible to be controlled is start and stop of the simulation. This action can be performed by clicking the toggle button next to *UNIT ON/OFF* label.

6.1.2 The units page

This page is separated via tab pane into three other pages. The first page displays the simulation process in the air-handling unit, the second one contains the FCU and the last one contains all the data.

Only the first tab is important in case of controlling. The others does not allow any setting possibilities.

The EagleHawk tab

This is probably the most important screen of all. On this screen all details about simulation and all possible settings are displayed.

The whole page contains:

- button for simulation start and end,
- button to move between other pages:
  - the alarm page,
  - the charts page,
  - the scheduler page.
- Area dealing with exterior conditions setting.
  In the homepage it is able to set only winter or summer default design conditions. Here it is also possible to set more accurate conditions depending on the user's will.
- Required conditions for interior.
  These values are possible to be set only in the case of occupied room and manual control. In other case these values are set automatically.
- Switch between manual control and scheduler
  It provides option to the user to choose between manual or automatic control which is set before.
- Default interior conditions setting.
  This setting is allowed only in case of stopped simulation.
- CO_2 concentration limit exceeded/OK.
- Occupation of the room.
  This setting has influence over the interior required values.

Every simulation starts with switching the *ON/OFF* button into *ON* state. After that the default conditions for interior and exterior are taken as the inputs for simulation.

The progress of the simulation can be controlled by occupation or CO_2 concentration and also by changing required values for interior.
The results can be shown in the charts page or if the user wants to see directly the progress of interior temperature or relative humidity, it is possible to click on them in the interior area. After clicking it is transferred directly to a separate chart depending on chosen variable.

All these settings are also possible to be done directly via workplace.

The graphical visualization of individual section:

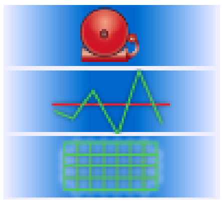

Figure 35 From the top: 1. The alarm page, 2. The charts page, 3. The scheduler page.

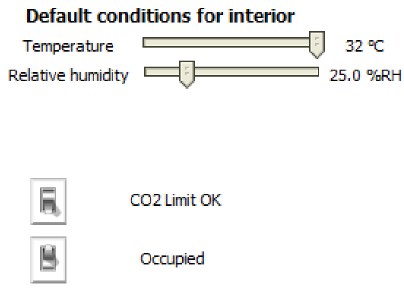

Figure 36 The interior settings.

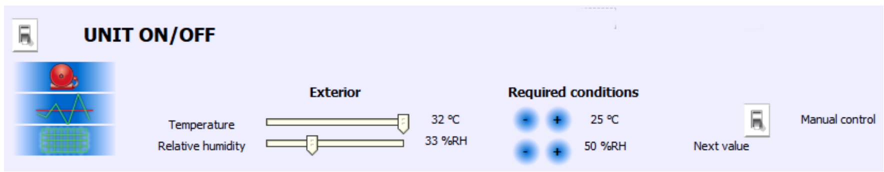

Figure 37 The exterior and required values setting.

6.1.3 Charts

The chart page allows the user to see the interior and exterior temperature with relative humidity in the first tab and the heater, chiller and humidifier load in the second tab. All these values can be zoomed by marking the specific area with mouse. Also it is possible to download the progress as a screen or the values into table, text or csv format.

6.1.4 Alarms

One of the most important pages in real practice. The design of this page is stable and it can not be changed, but it is not necessary, because it contains all possible informations about alarms.

It is up to the programmer, which values is necessary to observe and record as an alarm. In this application it is possible to record many values which can cause an alarm, e.g.:

- exceeded numerical value,
- change of boolean status,
- timed out.

All these values are possible to be adjusted to user satisfaction. Alarm record is possible to recognize according to its label, find out the time of record and other details. The alarm page also provides the history of alarms.

Among the other functions, the alarm interface provides:

- Silent the alarm notice,
- show alarms in specific time range, e.g. today, last 24 hours, last week, month.
- add a notes to specific alarm,
- filter alarms according to specific criteria.

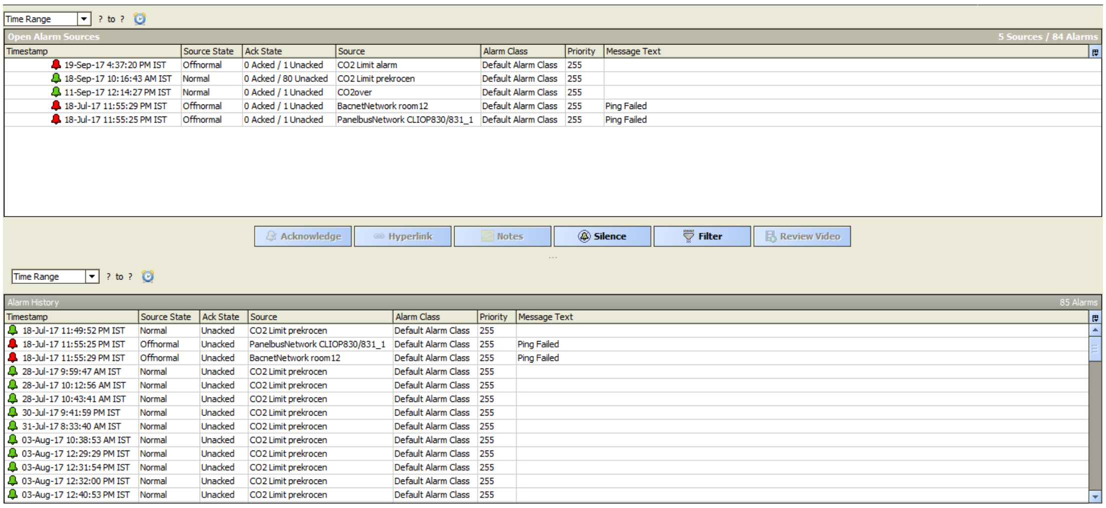

Figure 38 The alarms page.

6.1.5 Scheduler

The last page, which allows to use some setting is the scheduler. As in case of alarm page, this page is also designed directly by the hardware provider, so this study is only using its function.

The function of the scheduler is very useful in the real world, when the users can set a required value a long time ahead and also set repetitions.

This page has very simple settings, where the user only marks the specific areas in required days and hours with proper values. This function also support:

- Daily setting,
- weekly setting,
- working days + weekend days setting.

In case of some special events, its also possible to set this event in specific tab for interrupting the normal process of scheduler control.

This study provides scheduler for interior temperature as a presentation of hardware abilities. To scheduler activation is necessary to switch the toggle button in the units page, the EagleHawk tab to position *Scheduler*.

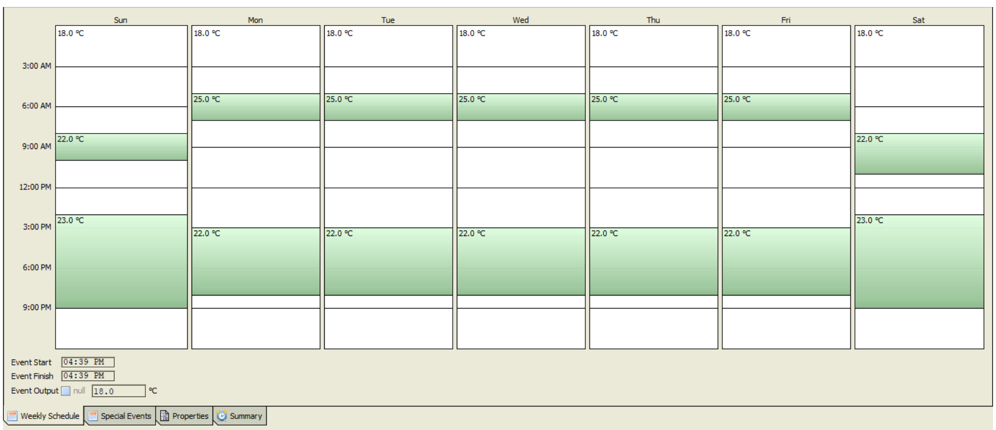

Figure 39 The scheduler page.

Basically, these pages create whole GUI which is approached by the user.

The first one, the homepage, should provide the user the basic information about processes inside both unit and information about collected values from the electricity meter and from the thermostat. This page does not provide detailed information about inside of the AHU unit, as the temperatures and relative humidities after elements. Also the air flow volume is possible to be found only in the units page. Among the others, this page provides the possibility to switch to every available page. The units page is possible to be obtained using the button with proper image. The switch to the chart page is conveniently set the whole area of chart as a hyperlink button. The last one, the alarms page is available via picture of light bar. The available settings are only for simulation, namely winter/summer default design conditions and default interior state.

The other page created in this study is the units page. This page provides detailed information about processes inside the AHU and FCU. There are also available all possible settings for simulation, e.g. required temperature, manual/scheduler control, CO_2 concentration, occupation etc. There is also one page dealing only with collected informations from units, the electricity meter and from the thermostat.

The last created page is displaying charts. In the dashboard values of interior/exterior temperatures and relative humidities and loads of the heater, chiller and humidifier are available.

7 Evaluation of function

This chapter deals with the evaluation of the whole workplace function. The evaluation can be separated into three parts:

1. graphical user interface,
2. the simulation,
3. the FCU reaction.

All these parts together create the whole demonstration workplace.

7.1 The graphical user interface

The GUI was created according to common practice and knowledge. All pages, which were created directly for this workplace, has uniform design as is possible to be seen in chapter 5.

The homepage is separated with different shades of blue and with combination of white and black texture is provided for good recognition.

The most important part in case of already designed dashboard are fonts. It is necessary to know where and in which conditions the application will be used. The colors of the fonts can be different, for example on wide flat screen, PC monitor or on projection. These things can be evaluated only directly at the place and have to be adjusted during the final realization. This study is designed on PC monitor and hence there is no problem with recognition.

In case of the other pages the same uniform design of interface and buttons is adhered to. Only in the case of used elements is an exception, because there are different graphical modules used for homepage and for units page to show the possibilities of the default modules.

The GUI also provides the possibility to change the language between Czech and English, which is very convenient in case of usage of this workplace in countries other than Czech Republic.

The whole graphical user interface is designed with extensive use of images instead of text. Due to this practice it is very easy to recognize the purpose of individual elements.

Also in these days of touch displays it is common to search for other abilities under every element of the dashboard. In this dashboard many elements are designed with this function, where for example charts part on the homepage after clicking take the user directly to the charts page which provide better resolution, and also other functions for data usage.

As has been mentioned before, this workplace is reachable via WiFi and common internet browser, so the dashboard and simulation were tested both on PC screen and tablet device. The usage via tablet device is not so comfortable as via PC, but in real practice can be used for unexpected checking from every place where the connection to the proper unit is available.

7.2 The simulation

The other part of the evaluation is dealing with simulation. The testing is divided into several parts according to season. For credible tests the loss and heat gain of the building are included and also reaction of the devices is delayed as a simulation of opening/closing the controlling valves.

Every season is tested based on:

- default design conditions,
- randomly chosen conditions,
- changes during simulation.

For every test the values of the interior and exterior temperatures and loads of devices are collected.

7.2.1 Winter season testing

Testing in winter season is mentioned here. In winter, it should be remembered that, not only is the action of the heater necessary but also action of the humidifier. As is possible to see in the H-X diagram, during heating it is possible to reduce the humidity of the air. So for the test adjust both temperature and relative humidity.

Reaction to default design conditions

Default conditions The main test is the simulation based on default design conditions. This conditions were used for designing the whole air-handling unit, so the unit should be able to compensate the imaginary losses of the building and reach the stable state.

The default conditions are:

Exterior parameters		
	Temperature t_e	$-15°C$
	Relative humidity φ_e	100%
Required interior parameters		
	Temperature t_i	$22°C$
	Relative humidity φ_i	30%
Default interior parameters		
	Temperature $t_{i,d}$	$0°C$
	Relative humidity $\varphi_{i,d}$	100%

Table 3 Table of default conditions for winter testing 1.

During the design occupancy in the room was calculated along with mixing. Based on this, the CO_2 concentration limit is set as *OK* and occupancy as *Occupied*.

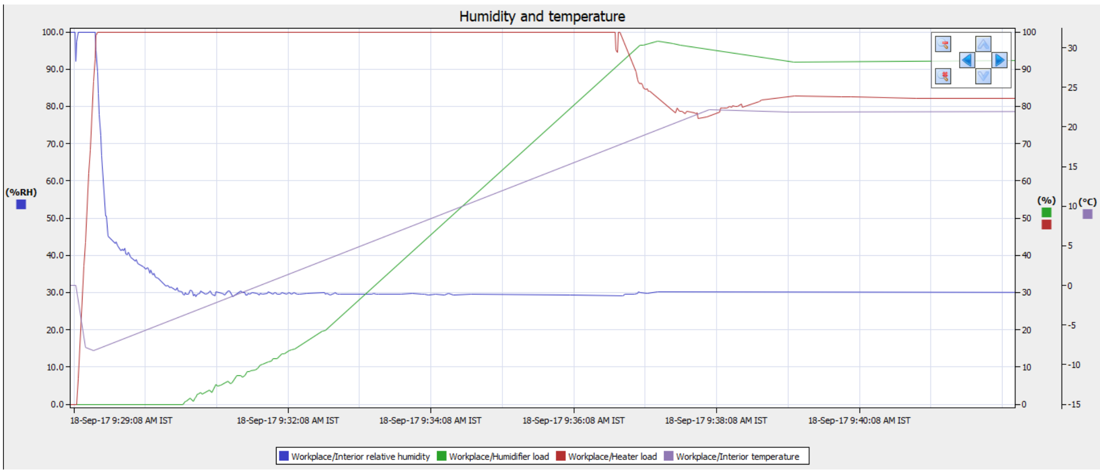

Figure 40 The heating - reaction to default design conditions

Evaluation of process - the result of test is shown in the chart 40. This chart contains all details involving the devices, the heater and the humidifier.

As is seen in the chart, the simulation starts at the moment of the first reduction in the interior temperature. This reduction is caused by the heat loss calculation which is incorporated into the simulation after the start. After that occurs the rapid rise of the interior temperature due to the heater action. While approaching the required interior temperature, the heater starts to react and the value of interior temperature starts to settle. With little overcome the interior temperature is fluently settled to the required value.

The inside relative humidity on start moves very quickly to lower values, which is also caused by the influence of heat losses in combination with the processes happening inside the unit. After that the humidifier reacts to the increase in load and the humidity starts to settle. In combination with temperature settling the relative humidity also finally settles to the required value.

All the parameters are settled approximately after $12 minutes$.

Reaction to change during stable state

The second test is about changing a required value during stable situation. This situation is probably the most common situation in winter, when the users want to change the pre-set value of temperature for higher comfort.

Default conditions - this test follows the last one so the exterior conditions are still the same. The unit is tested for both, temperature rise and temperature reduction. At first the temperature rise is provided and after that the return to default conditions follows.

Exterior parameters		
	Temperature t_e	$-15°C$
	Relative humidity φ_e	100%
Required interior parameters		
	Temperature t_i	$24/22°C$
	Relative humidity φ_i	30%
Default interior parameters		
	Temperature $t_{i,d}$	$22°C$
	Relative humidity $\varphi_{i,d}$	30%

Table 4 Table of default conditions for winter testing 2.

Also in this case of the test it is assumed that the room is occupied and the CO_2 concentration limit is not exceeded.

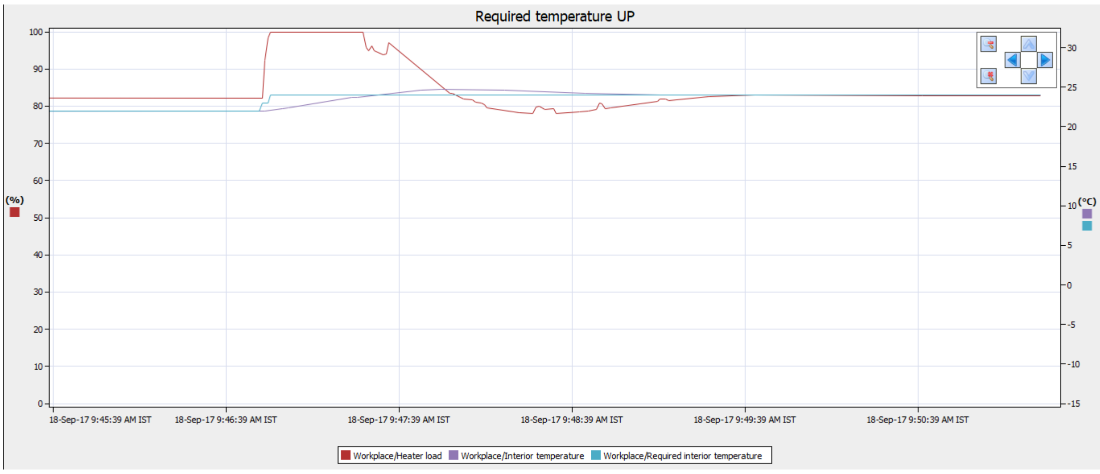

Figure 41 The heating - temperature raise

Evaluation of the temperature rise is based on the progresses shown in the picture 41. This chart contains the actual interior temperature, the heater load and also required interior temperature. From the last noticed value it is possible to see the time of change. Immediately with the change of required temperature it is possible to see the reaction of the heater which is, in these exterior conditions, loaded at first to 80%, so the the path to full load does not take much time.

After a proper interior temperature reaction it is possible to see the effort of the heater to rapid settling of the interior temperature. According to chart, this value is, again with small overcome, fluently settled.

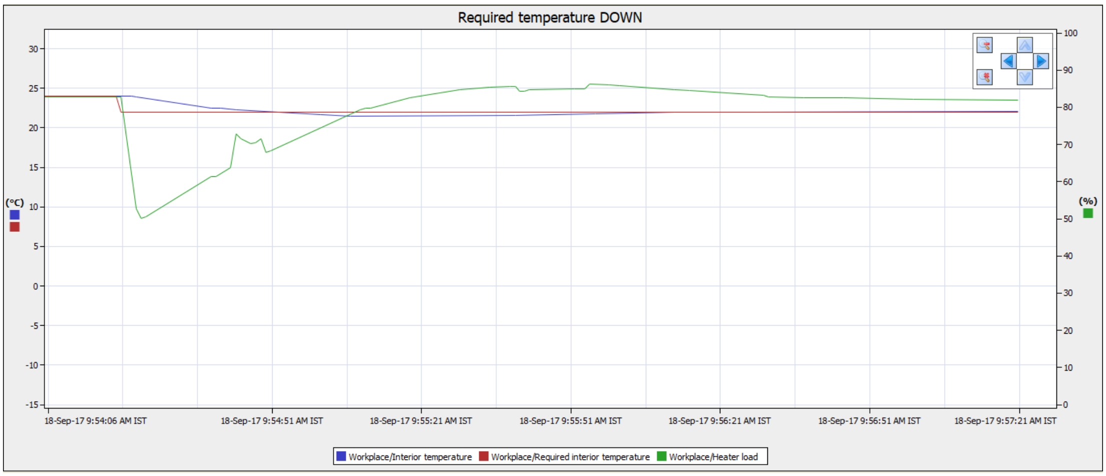

Figure 42 The heating - temperature reduction

Evaluation of the temperature reduction is the simulation following the previous one. In this simulation the goal reaches again the stable state on $22°C$. In the chart 42 it is clearly seen the moment of required action based on the required interior temperature. With small delay is this change followed by the heater reaction and reaction of the interior temperature. After the heater load change, the interior temperature gets lowered to the required value. After a short time, approximately after $3minutes$ which is necessary to reach the proper interior temperature, the interior temperature gets settled right on the required value.

Reaction to change in the occupancy rate

This test is about reaction of the simulation to change in the occupancy status. In the beginning of the test the room is stabilized to normal required parameters, after switching on the toggle button, the required parameters are changed to various values and whole unit starts to react. After stabilization the return to default design conditions is also tested.

Default conditions - as has been mentioned before, default parameters are based on the design values. The test is about change of the required interior temperature and humidity.

Exterior parameters		
	Temperature t_e	$-15°C$
	Relative humidity φ_e	100%
Required interior parameters		
	Temperature t_i	$22/18/22°C$
	Relative humidity φ_i	$30/35/30\%$
Default interior parameters		
	Temperature $t_{i,d}$	$22°C$
	Relative humidity $\varphi_{i,d}$	30%

Table 5 Table of default conditions for winter testing 3.

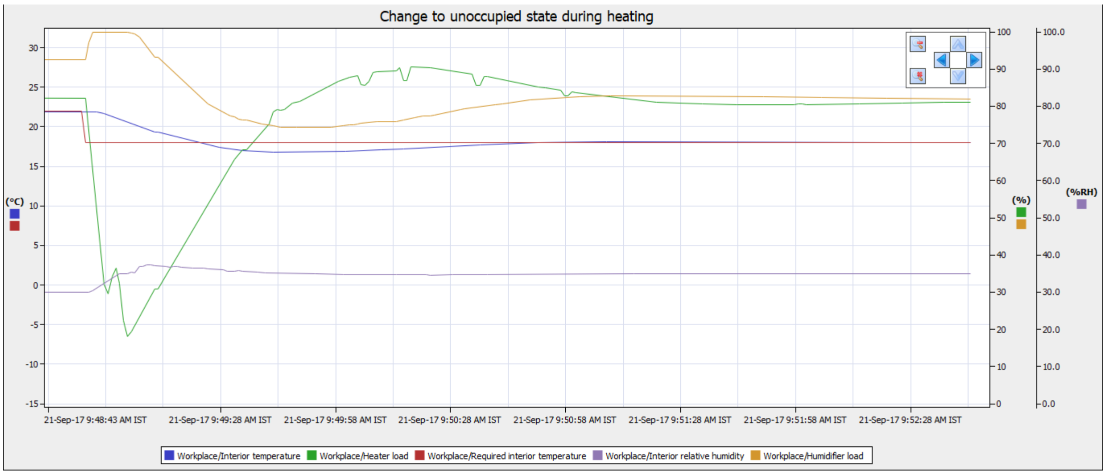

Figure 43 The heating - change the occupancy state

And the return to default design conditions:

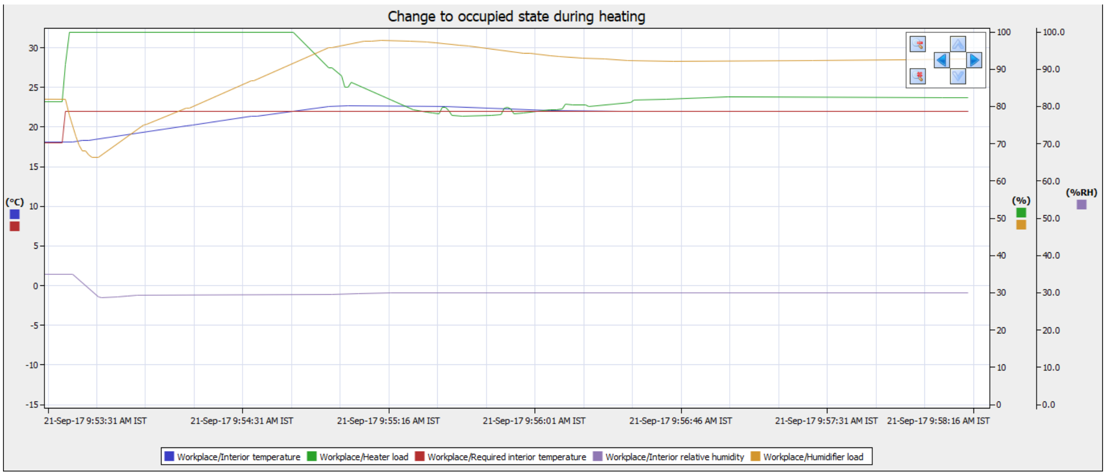

Figure 44 The heating - change the occupancy state

Evaluation of processes. The first test begins with change of the required interior temperature. With short delay it is possible to see the action of the heater and the humidifier, and hence the change in the interior temperature and relative humidity. As in the case of the second test, the result is similar. Both interior temperature and relative humidity are settled in combination with settling of the heater and humidifier right on required conditions.

The return to default design conditions has also the same result as in second test. Approximately after 3.5min all the values are settled on the required values.

Evaluation of function via the Mollier Diagram

The last section about heating is evaluation of the function of the whole calculation in simulation in comparison with the calculation via the Mollier diagram. The diagram can be seen in full size in appendices. The result is verified after settling of all observed parameters, i.e. interior temperature and relative humidity. For verification, the last state of the air before reaching the room is used.

Default conditions are the same as the default design conditions.

Exterior parameters		
	Temperature t_e	$-15°C$
	Relative humidity φ_e	100%
Required interior parameters		
	Temperature t_i	$22°C$
	Relative humidity φ_i	30%

Table 6 Table of default conditions for winter testing 4.

In this test it is necessary to have both CO_2 concentration and the occupancy in the default states, so the limit is not exceeded and in the room full occupancy is presumed.

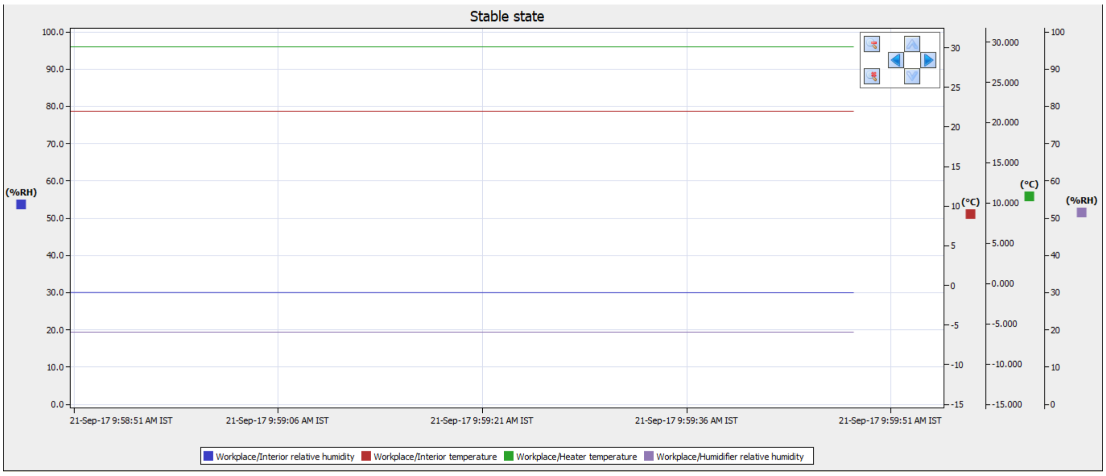

Figure 45 The heating - stable state with observed parameters

Evaluation of process. The gain of this test is that it approves the correctness of the calculation inside the unit. For evaluation the parameters from the H-X diagram for winter season and the results of simulation from the chart 45 are used.
All the values are compared in the following table:

	The Mollier's diagram	The simulation
Temperature after heating	$30°C$	$29.4°C$
Relative humidity after moistening	18.8%	19%
Reached interior temperature	$22°C$	$22°C$
Reached interior rel. humidity	30%	30%

Table 7 Table of results

As shown in the table the parameters have expected values. The small differences are caused by rounding off during the calculation. According to these values it is possible to presume that the simulation of the heating works properly.

7.2.2 Summer season testing

The next section is about testing during summer season. In summer the major attention goes to the chiller. It is obvious from the H-X diagram that in this season the activity of the humidifier is not necessary because the changes of the interior temperature provides, with proper parameters, the right change in the interior relative humidity. The list of tests is similar as in the case of winter season.

Reaction to default conditions

As in case of the winter season the first test is about reaction to default conditions and observing the changes.

Default conditions. As the default conditions it is necessary to use the same parameters as in the case of the design of AHU. In this situation the unit should be able to compensate heat gains and required changes from user. The default conditions are:

Exterior parameters		
	Temperature t_e	$32°C$
	Relative humidity φ_e	33%
Required interior parameters		
	Temperature t_i	$25°C$
	Relative humidity φ_i	50%
Default interior parameters		
	Temperature $t_{i,d}$	$32°C$
	Relative humidity $\varphi_{i,d}$	33%

Table 8 Table of default conditions for summer testing 1.

During the design calculation was done with occupancy in the room and also with mixing. Based to this, the CO_2 concentration limit is set as *OK* and the occupancy as *Occupied*.

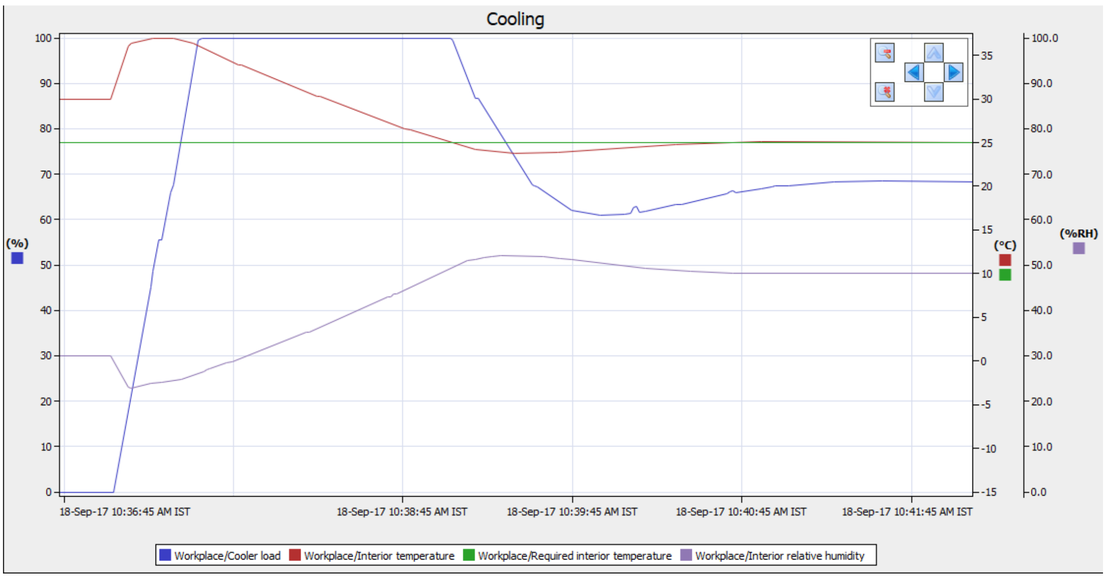

Figure 46 The chilling - reaction to default design conditions

Evaluation of process. The whole test begins with change in the interior temperature. The first impact to this temperature occurs due to the heat gain activation which increases the interior temperature to higher values. At the same time the chiller is activated and the interior temperature reacts this causing reduction in value. The next value in the chart is the interior relative humidity which also reacts to changes in the test. In the summer season the humidifier is not available so the value of the relative humidity is depending only on the interior temperature state. Approximately after $5minutes$ all the variables are settled. As is seen in the chart, the interior relative humidity is not settled accurately on the required value. This can be caused due to too many rounding off in the process of calculation and design. However, this inaccuracy shouldn't have any affect in the real work and it shows what effect rounding off can cause.

Reaction to change during stable state

The next text is about changing the required parameters during the stable state. This test probably present the most common situation in reality when the user wants to change for example the required temperature in the room.

Default conditions. During this test temperature reduction as well as rise in temperature are both presented. As in the case of winter season the changes are in the scope of $2°C$.

The default conditions are:

Exterior parameters		
	Temperature t_e	$32°C$
	Relative humidity φ_e	33%
Required interior parameters		
	Temperature t_i	$25/23/25°C$
	Relative humidity φ_i	50%
Default interior parameters		
	Temperature $t_{i,d}$	$25°C$
	Relative humidity $\varphi_{i,d}$	50%

Table 9 Table of default conditions for summer testing 2.

Also in this case of test it is the assumed that the room is occupied and the CO_2 concentration limit is not exceeded.

Evaulation of the processes. Both processes (figure 47 and 48), after certain time, reach the required interior temperature.

In case of reduction of the required temperature it is possible to see that the parameter is settled after $2minutes$. The part of the chart has also the value of the interior relative humidity. This parameter is, as has been mentioned before, driven only by the interior temperature adjustment. In this case the settled value is different than the required value. In settled state it is possible to measure $55\%RH$. This is the presumed result, because in case of the temperature reduction the curve of air state in the H-X diagram is moved down to higher values of the relative humidities.

The following process is about returning to default design values. Again after $2.5min$ all the parameters reach approximately the presumed states.

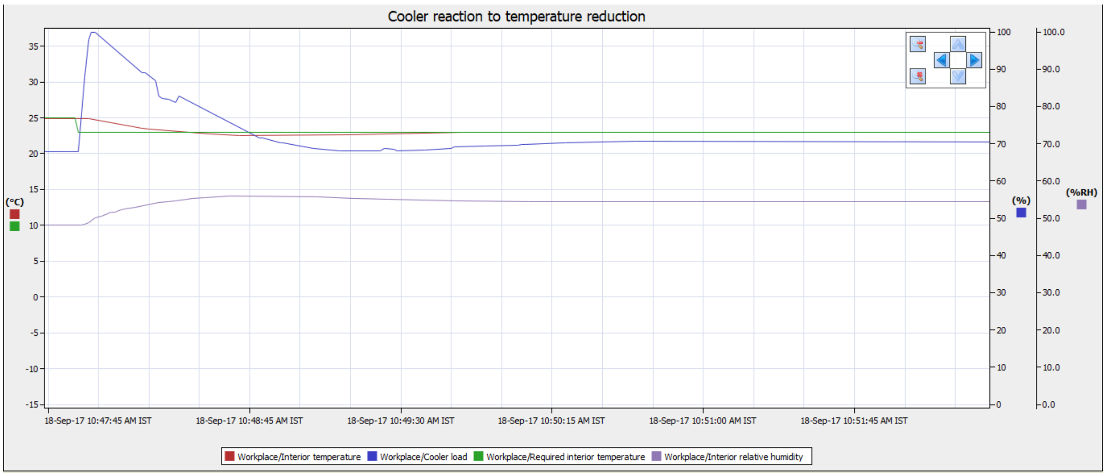

Figure 47 The chilling - reaction to the required temperature change.

And the reaction to the required temperature rise:

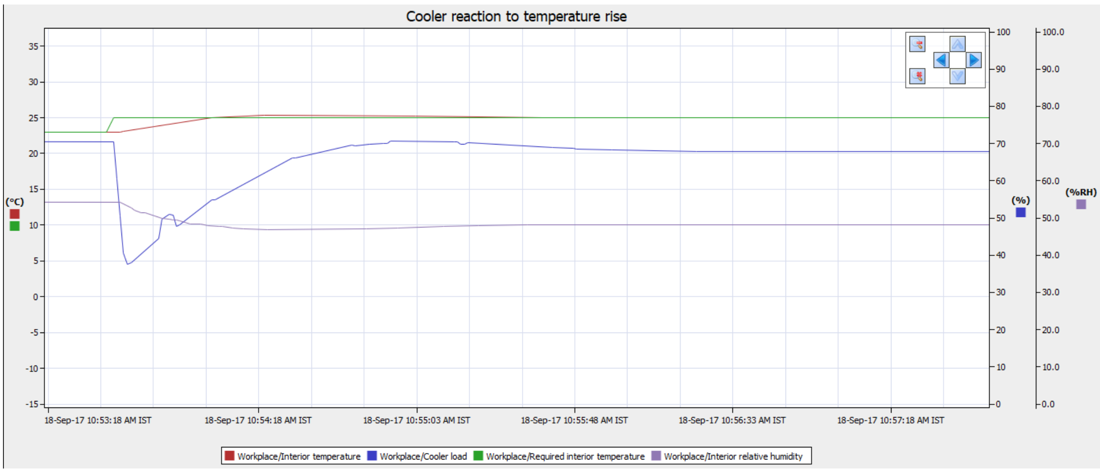

Figure 48 The chilling - reaction to the required temperature change.

Reaction to the change in the occupancy rate

The third test is about reactions to changes in the occupancy state. The changes are in both the required interior temperature and relative humidity.

Default conditions. Basically this test is the same as the previous one with small temperature difference. The difference is also in required changes as in case of this test the interior relative humidity is also observed, which depends directly on the interior temperature.

Exterior parameters		
	Temperature t_e	$32°C$
	Relative humidity φ_e	33%
Required interior parameters		
	Temperature t_i	$25/26/25°C$
	Relative humidity φ_i	30/35/30%
Default interior parameters		
	Temperature $t_{i,d}$	$22°C$
	Relative humidity $\varphi_{i,d}$	30%

Table 10 Table of default conditions for summer testing 3.

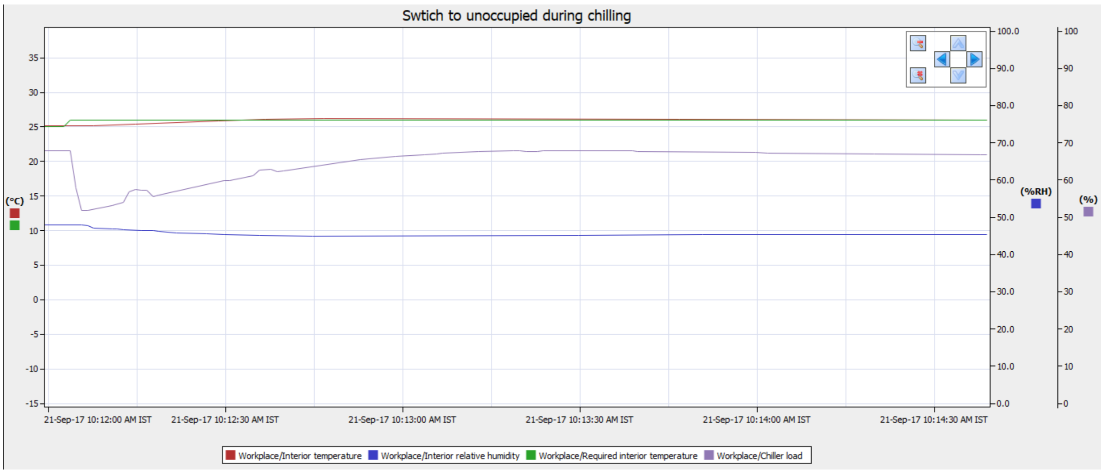

Figure 49 The chilling - change the occupancy state

And the return to default design conditions:

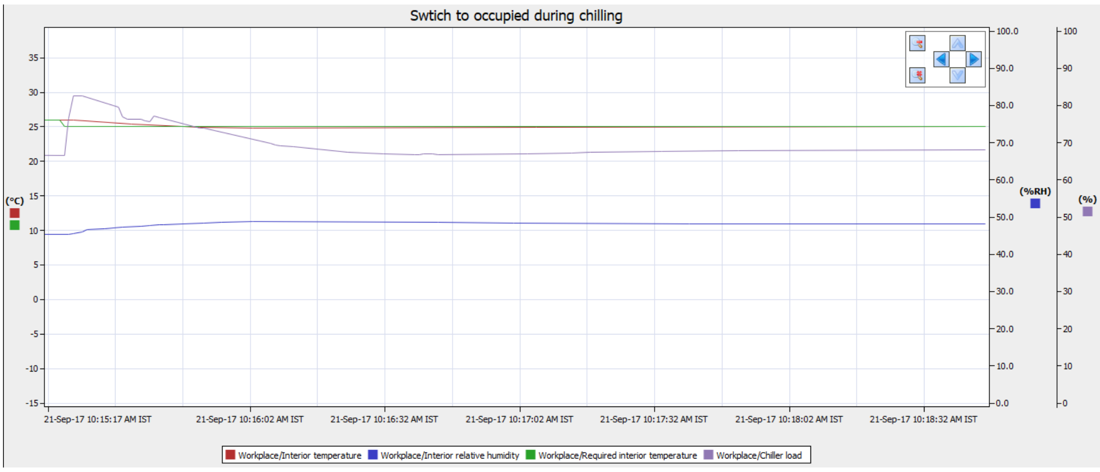

Figure 50 The chilling - change the occupancy state

Evaluation of processes. In both processes the interior temperature is settled on the required temperature. The relative humidity has presumed progress and its final value in not equal to the required one. However, it is not so important, because the unit only follows the process in H-X diagram and without action of the humidifier or other options for humidity adjustment it is not possible to set the value accurately. In the end, this value of the relative humidity is still in comfort zone for following occupancy.

After switching back to state *Occupied* the values are settled back as in the default state.

Evaluation of function via the Mollier Diagram

The last section deals with the evaluation of the function of the chilling via comparison with the Mollier diagram. The Mollier diagram for the summer season is shown in full size in appendices. The evaluation is done after the AHU is settled in stable state on the required parameters. For verification the state after last change of air is used, i.e. the relative humidity after chilling and the temperature after chilling.

Default conditions are the same as the default design conditions.

Exterior parameters		
	Temperature t_e	$32°C$
	Relative humidity φ_e	33%
Required interior parameters		
	Temperature t_i	$32°C$
	Relative humidity φ_i	33%

Table 11 Table of default conditions for summer testing 4.

In this test it is necessary to have both CO_2 concentration and the occupancy in the default states, so the limit is not exceeded and in the room is presumed the have full occupancy.

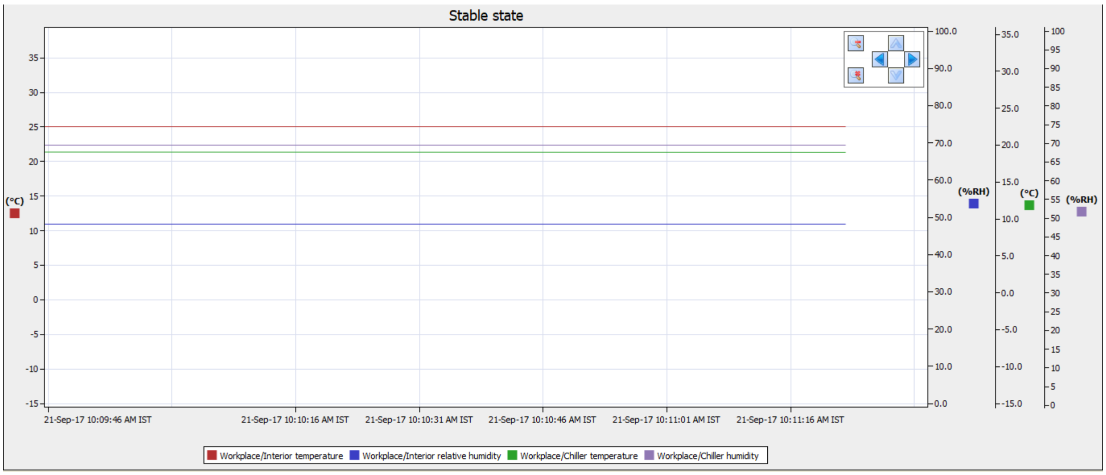

Figure 51 The chilling - stable state with observed parameters

Evaluation of process. The gain of this test is that it approves the correctness of the calculation inside the unit. For evaluation the parameters from the H-X diagram for summer season and the results of simulation from the chart 51 are used.
All the values are compared in the following table:

	The Mollier's diagram	The simulation
Temperature after chillig	$20°C$	$19°C$
Relative humidity after chilling	61.14%	69%
Reached interior temperature	$25°C$	$25°C$
Reached interior rel. humidity	50%	48%

Table 12 Table of results

As it is seen in the table the biggest difference is in the relative humidities. The difference between the Mollier diagram and the simulation after chilling causes the difference in the final state. The problem is possibly also in the rounding off because the movement of air in the unit is calculated by absolute humidity and not relative. To get the relative humidity it is necessary to calculate with already rounded values. However, with more accuracy the whole calculation process will be more and more demanding and in case of the demonstration workplace, as is this case, it is not appropriate count with accuracy as high as possible. The interval in which the differences occur is not so large and is satisfactory.

7.3 The fan-coil unit

The fan-coil unit graphic environment is the last part of the evaluation. In this case only the proper reaction of the GUI is necessary followed by reaction of physical elements as the LED diodes. Every reaction in this case is driven by already programmed strategy in the IRC controller. In this study proper setting of this strategy and connection between physical elements in the workplace and between the GUI is only necessary. The reaction on one of the statuses is provided in the following picture.

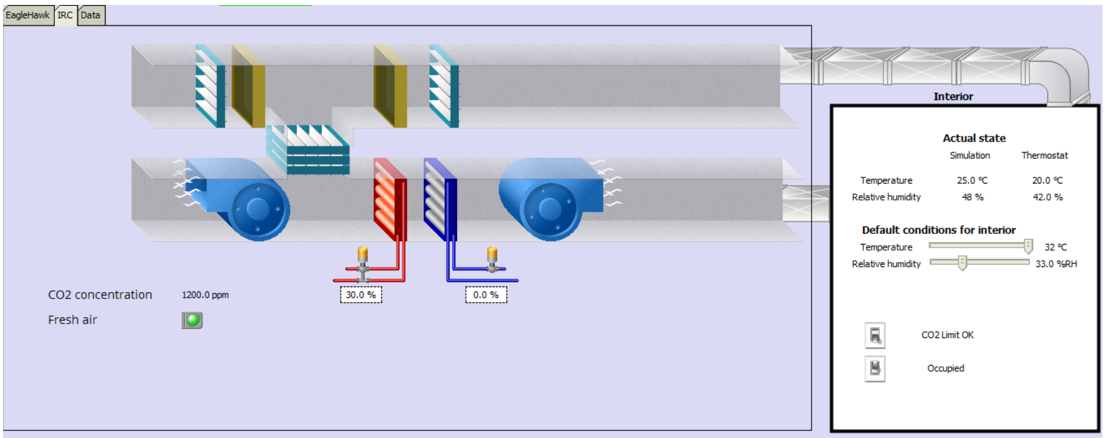

Figure 52 IRC reaction in the GUI

As you can see the reaction is in winter season, when the required temperature is higher than actual. Due to this, the heater is showing proper reaction. Also the CO_2 concentration limit is exceeded, so the label of *FRESH AIR* is *ON* and the unit commands to supply the interior with higher amount of fresh air.

This GUI is showing the detailed information as in case of AHU. The GUI placed on the homepage has the same graphical visualization as the air-handling unit so there are no details.

8 Conclusion

The goal of this thesis is to design and build a complete demonstration workplace for two controllers, the EagleHawk and the IRM. Workplace should contain both controllers, other necessary devices and several elements which allow proper representation of the action to the user. The other part of the thesis is the graphical user interface which should also present all possible states and also the various abilities of the used software. The whole workplace should be available in both wired connection and wireless connection also. For the purpose of the presentation two units from air conditioning scope were chosen - air-handling unit and fan-coil unit. Both of the units are figured in the mode of diagram. One of them, the AHU, is presented using simulation when the all processes inside the unit are simulated and the reactions are based on parameters set by user. The FCU unit uses the abilities of the thermostat and shows to the user the reactions to the actual conditions in the room.

The first part, which was necessary for building the workplace, deals with designing and processing the workplace visualization. As is seen in the second chapter, for purpose of presentation a suitcase was chosen which is easily transportable and also provides enough space and several possibilities to achieve demanded goals. During the design $3D$ modeling was used for getting better imagination about final visualization. After finishing the realization several changes were made caused by the changes in case of the workplace configuration. In the end, the whole suitcase contains two controllers, I/O module, electricity meter with A/D converter, router and power supply for devices charging and thermostat. This part also contains the description of all of these devices.

The physical realization is followed by design of the environment. This part is divided into several sections which builds step by step the parameters of the both units and also mathematical base for the simulation. At first the design of the building which is used for the design purpose is presented. It is necessary to design parameters of the area, as heat gain and loss, also the size of the place, the construction of the building etc. For purpose of this study specialized design tools were used which brings only a distorted view in the reality but for the purpose of this study are satisfactory. This chapter also contains the description of individual elements behaviour during air adjustment and which types were selected for the purpose of the design. The last thing which is necessary to design an air conditioning unit are the default design conditions which depends on the place of the building. For this study the edge of Prague was chosen as the location. With all this knowledge it is possible to design units parameters for both summer and winter season. For the design Mollier diagram was used which is commonly used for designing the units in the Czech Republic.

With the parameters of the units it is possible to design proper strategy for the units. The FCU has strategy already build inside the controller, so there is nothing to change. This unit simply reacts to area interior temperature and adjust the supply air according to this value. The second parameter which is important for this unit is CO_2 concentration limit which controls the volume of fresh air for the room. On the other hand, in case of the simulation, it is possible to set the strategy from the beginning. This strategy is designed for comfort inside the zone of administration building, also takes into account the CO_2 concentration as in the case of the FCU, but the strategy also depends on other parameters. Among the mentioned parameters is also the interior occupancy, where the simulation shows a different setting in case of unoccupied room and also provide the opportunity to drive the unit via scheduler or manual control. This chapter contains a description of the strategy for every individual element of the unit and also brief introduction of the controllers used for driving heating, chilling and humidification.

For proper presentation it is also necessary to have a well build graphical user interface. In this study the GUI is designed based on several principles and knowledge which should help the user to faster recognition and better understanding of the whole dashboard. Also because of the main goal of this study, the presentation of abilities, the whole GUI contains a several pages divided according to purpose, i.e. homepage, units page with individual tab for AHU, FCU and collected data and also chart page, alarm page and scheduler page. In this chapter the service dashboard is also shown which was used for the strategy evaluating process. As the whole GUI contains a lots of possibilities, the next chapter deals with the description of the controlling and understanding the processes inside the dashboard.

The last part of the study deals with evaluation of the workplace function. This evaluation is divided into three parts, GUI, simulation and FCU part. In the GUI part the reasons of the chosen visualization are mentioned along with the processes of evaluating in reality, where the whole GUI should be tested in real conditions and adjustment to final stage according to requirements of the specialized user. The only way to evaluate the simulation is by showing the results of the processes. Four reaction of the unit are shown for winter season and the other four reaction for summer season. These tests were based on reaction to default design conditions, reaction to the change in interior required temperature, reaction to the change in occupancy status and also comparison of stable state with values from the Mollier diagram which was used for the design. In all these tests behaviour of the unit was obtained as expected with small inaccuracies. The biggest inaccuracy was in case of the interior humidity in summer season. This inaccuracy could be caused due to rounding off during the calculation and design because in the other cases the humidity behaviour is as expected. The last part deals with evaluation of FCU function, when the reaction which GUI only provide is the graphical presentation. All states are presented in the proper way and because the design of the strategy for this unit is not part of this study, the graphical reaction is only shown.

The whole workplace is possible to be controlled in cooperation with physical elements placed in one of the covers and also with graphical interface. As is mentioned in the thesis, the controlling environment is available via WiFi with the help of the router so the dashboards are available everywhere signal is available. Also due to the proper design the whole dashboard is possible to be controlled by both computer and touch display and it is not necessary to have special software but only a common internet browser.

Appendix A

Pictures

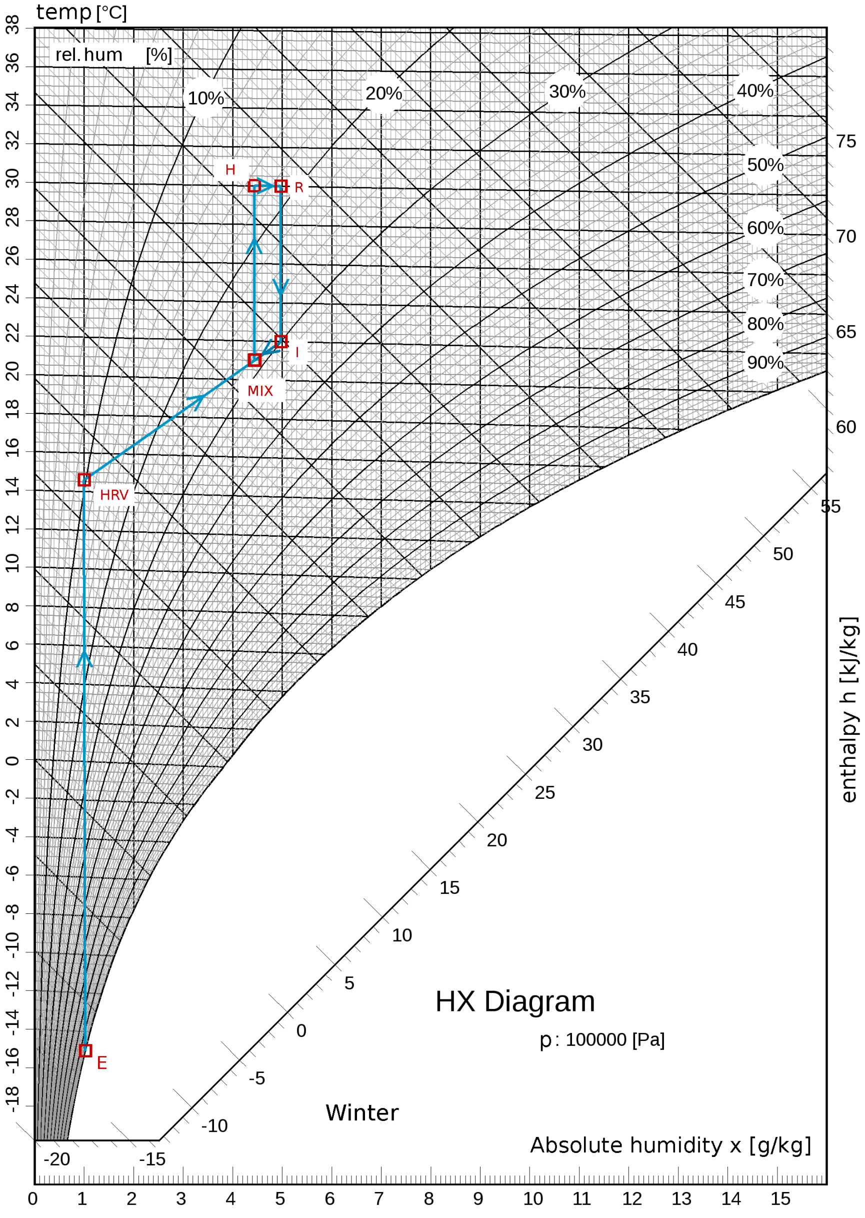

Figure 53 H-X diagram for winter season

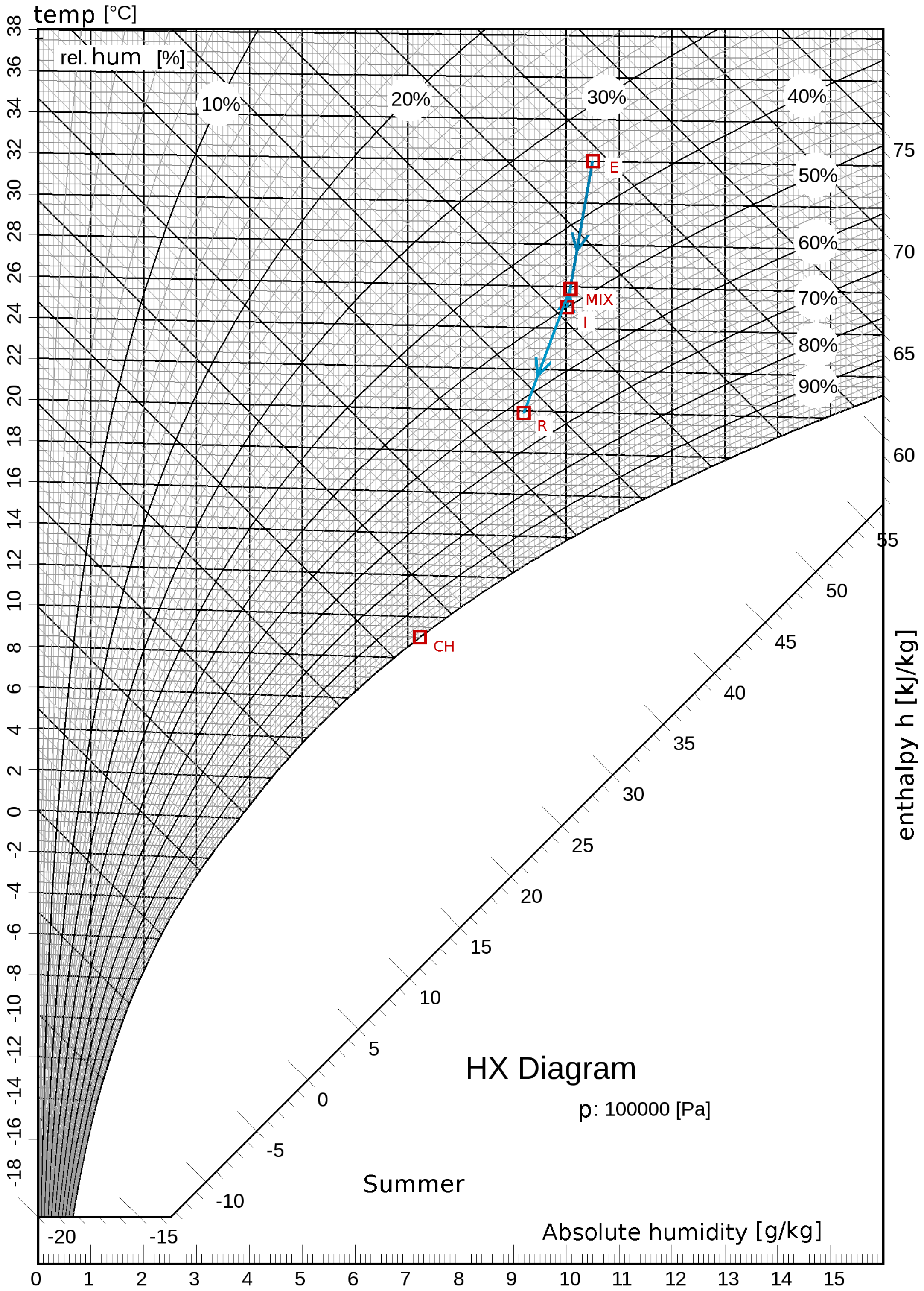

Figure 54 H-X diagram for summer season

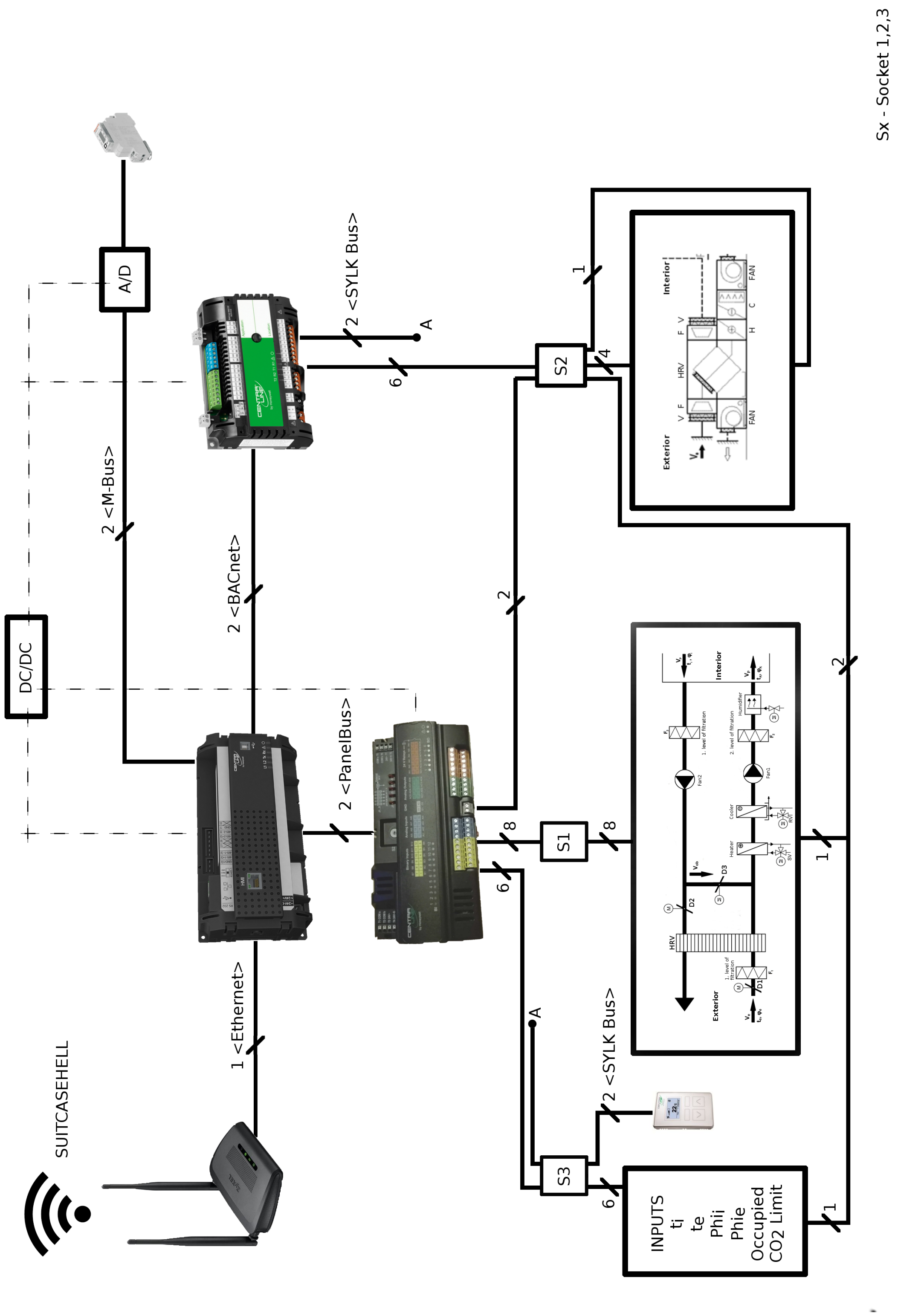

Figure 55 Scheme of workplace

Appendix B

Inputs/Outputs wire description

Air-handling unit scheme				
The name of Element	Controller	In/OUT	Socket	Wire color
$K1$	I/O Module	$AO1$	$S1$	blue-white
$K2$	I/O Module	$AO5$	$S1$	brown-white
$K3$	I/O Module	$AO3$	$S1$	orange
HRV	I/O Module	$AO2$	$S1$	blue
Heater	I/O Module	$AO6$	$S1$	brown
Chiller	I/O Module	$AO7$	$S1$	green-white
Humidifier	I/O Module	$AO8$	$S1$	green
Fans	I/O Module	$AO4$	$S1$	orange-white
Ground	I/O Module	GND	$S2$	orange-white
Fan-coil unit scheme				
Fans	IRM	$AO1$	$S2$	blue-white
Fresh air	IRM	$AO2$	$S2$	orange
Heater	IRM	$AO3$	$S2$	green-white
Cooler	IRM	$AO4$	$S2$	green
Ground	IRM	GND	$S2$	brown-white
Inputs				
t_i	I/O Module	$AI8$	$S3$	blue
t_e	I/O Module	$AI3$	$S3$	orange
ϕ_i	I/O Module	$AI7$	$S3$	blue-white
ϕ_e	I/O Module	$AI4$	$S3$	orange-white
Occupied	I/O Module	$DI6$	$S3$	blue-white
CO_2 LIMIT	I/O Module	$DI5$	$S3$	blue
Ground	I/O Module	GND	$S2$	orange-white
Thermostat				
Sylk bus	IRM	$WM1/WM2$	$S3$	brown-white/brown

Table 13 The wire description

Where Ax means analog input-output and Dx means digital input-output.

Appendix C

CD contents

- DP_simicek_2018.pdf *Master's thesis.*
- stationWorkplace.zip *Station for EagleHawk controller.*

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