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Real-Time Integration of IEQ with BIM

User-Centered Approach

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Abstract of master's thesis

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Abstract

Altering indoor environment to increase occupants comfort may increase their productivity and reduce waste in time, energy and resources. This work attempts to understand occupants' behavior and comfort to build a platform that visualizes user-centered parameters related to indoor environment in real-time using IoT. User-centered prototype platform was designed, built and tested. Gamification concepts was applied to increase participation. The results were visualized and spatially mapped to the 3D model. This platform may help users build better perception about their indoor environment, i.e. in offices, schools, hotels and hospitals, using interactive content and games. Also, it may help decision makers to take faster and better decisions, relying on the abundance of user-centered data, which may help in quality improvement.

A test with around 20 users was made to assess indoor and learning environments. Many have found the system useful and easy to use on their mobile devices. Users shared valuable feedbacks and ideas for further developments. The first experiment gave important insights for possible future tests.

Keywords BIM, IC, IEQ, IAQ, IoT, UCD

Acknowledgements

Our shared breath and ancestor matters that keep us alive, what is me without you?

Espoo, May 20, 2018

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Abbreviations and Acronyms

API	Application programming interface
BIM	Building Information Modeling
BMI	Body Mass Index
CAD	Computer Aided Design
CFD	Computational Fluid Dynamic
DDP	Distributed Data Protocol
DOM	Document Object Model
GUID	A Globally Unique Identifier
gbXML	Green Building Extensible Markup Language
IAQ	Indoor Air Quality
IC	Indoor Climate
ICT	Information Communication Technology
IEQ	Indoor Environment Quality
IFC	Industry Foundation Classes
IoT	Internet of Things
NFC	Near-field Communication
npm	Node Package Manager
nZEB	nearly Zero Energy Building
PM	Particulate Matter
PMV	Predicted Mean Vote
PPD	The predicted Percentage of Dissatisfied
WHO	World Health Organization
UX	User Experience
RFI	Request for Information
RFID	Radio-frequency identification
SBS	Sick Building Syndrome
TOI	Transdermal Optical Imaging
UCD	User Centered Design
UI	User Interface
VRML	Virtual Reality Modeling Language

VR	Virtual Reality
x3d	Extensible 3D Graphics
ZNE	Zero Net Energy

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Chapter 1

Introduction

1.1 Problem statement

The periodical method of collecting information about occupants to assess their comfort has some limitations. Surveys are usually used to obtain data about user experience and their subjective opinion. However, users may not be interested to answer, accurately, long surveys frequently. The collected information, including the location, is stored usually in a database but are not modeled and managed as part of building information modeling/management (BIM) process. Professionals who need to understand and analyze the information are required to map the data back to the source of generation. By the time when the professional visualize the data manually on the 3D model, the findings may be different from the new current state of the building as these findings are based on the old data. Also the relationship between spaces and their IEQ is harder to observe in the tabular information than in the 3D mode.

Thus some recent literature [60] emphasize on the importance of integrating indoor environment quality within BIM. The usage of information and communication technology (ICT) and the internet of things (IoT) in smart buildings provide a persistent flow of real-time feedback from occupants concurrently with climate data about their living environment that could be analyzed to maximize comfort and increase energy efficiency. The subjective comfort in different places in the building give instant information about the parts of the building that may require attention and further comprehensive surveys and questioning.

Chapter 2

Background

Global warming and the rise in energy consumption around the world is stressing for stern regulation to reduce energy consumptions in buildings. Among all the energy consumed in the US, buildings share accounts for around 40% [13]. Reducing energy consumption could be achieved on the cost of indoor environment quality (IEQ) by i.e reducing the ventilation level inside the building. However, this will lead to worsening the comfort and rise in health problems. A better option is to research new ways of designing sustainable smart buildings to achieve nearly Zero Energy Building (nZEB) or zero net energy (ZNE) that rely minimally on the active energy systems. Such buildings are expected to provide comfort for occupants with minimal energy consumption.

People spend more than 90% of their time indoors [55]. Their productivity and well-being is strongly influenced by the quality of their living space. Sick building syndrome (SBS) is researched heavily since it was discovered in 1960, yet humans are unable to understand it comprehensively. It is expected that the cause of it is related to a combination of factors. The amount and quality of ventilation are proposed to be the most determining one. [50]. SBS is just one example of an illness that could be caused by living in unhealthy buildings. Respiratory diseases, allergy, and asthma are all on the list of possible diseases that are caused by improper indoor air quality (IAQ) [31]. The alteration of IEQ may monetize by lowering the expenditure on health treatments and consultation, promote sustainable ways of living, boosting the productivity and also the quality of life.

In USA, a study that was made around 1997 has found that altering the IAQ is expected to account for a maximum of 168billion USD savings annually. This benefit is 47 times more than the costs required to achieve the recommended IAQ[1] [31]. This is the estimated financial gain obtained

[1]The authors stated in the study that productivity is hard to quantify, yet they esti-

from better indoor air quality or better HVAC system. The additional gain that is expected to be achieved by considering indoor environmental factors, i.e. natural lighting, healthy materials was not estimated in the study. However, a review of more than 300 papers studied indoor physical and behavioral environment concluded that better IEQ renders better productivity and health [37]. This leads us to think that further annual savings could be achieved by adjusting additional elements in the indoor environment which did not yet get the same attention as the one given to indoor climate (IC) and IAQ.

The effects of thermal factors like temperature, humidity, and pollutants on occupants performance and health are well documented and widely studied during the last decades. Surveys, questionnaires, data obtained from sensors to assess the indoor climate and air quality in a controlled environment were commonly used. Achieving ideal thermal comfort with an acceptable level of pollutants, yet crucial, does not lead necessarily to high level of productivity, satisfaction and comfort. This is because comfort is not only related to the thermal environment but also involve some other physical objective and subjective factors like artwork. A review of 214 publications has found that music, visual environment, acoustic environment, ergonomics, among other factors, elevate well-being and health inside health care facilities [54]. It was also found that the existence of indoor plants reduces stress level [24].

The aforementioned shed a light on the complex relationship between humans and their physical environment. However, the psychological aspects, i.e mental state and social integration, just add additional complexity. It was found that daylights affect the rating of thermal comfort and on other hands thermal comfort affect the rating of IAQ [37]. Thus understanding such huge amount of relevant interconnected dynamically changing multidisciplinary parameters suggest that a stronger emphasize has to be put on the continuous collection of real-time data, information and feedbacks from people, as biological sensors, and their environment. This approach is centered around real-time sensing and receiving inputs from dwellers. High-speed wireless internet connections and the boom of smart devices that have accelerated the utilization of technologies such as wearable devices in addition to the advancement in building information modeling/management (BIM) would help us understanding occupants requirements and preferences better and fulfill them faster.

Many of the current standards endorse the added productivity that is achieved by improving the IEQ. However, few only add a score for buildings

mated that the minimum financial gain exceeded the cost by 14 times that fulfill such attributes. Thus, new building certifications standards that are centered around people satisfaction were founded in the last few years. WELL certification implies that the building should meet particular design and operation benchmarks and prompt healthy behavior to uplift health and well-being. The main areas of evaluation are air, light, water, nourishment, fitness, mind and comfort. [2] The lack of productivity and comfort assessment in the common standards is not the only limitation. There is barely any standard which observes the state of the building during its operational phase to check if the building preserves its parameters despite the changes of maintenance state, occupants numbers, activities and seasons. REST is one of the new standards that require real-time and longterm assess of IAQ [12]. Such new standards were born due to the extended understanding of the relationship between well-being and productivity and to tackle the indirect costs that are caused by living in an unhealthy buildings. The goal of this research comply with the recent studies recommendation of setting an innovative real-time system to collect data and widen our understanding of well-being and comfort and their effect on productivity. We further aim to spatial map the results and integrate them in the BIM to form a platform that could be used by professionals from HR and IAQ. In the future, a customized UI may be designed to help human resources understand employees satisfaction level in their oversees building and guide their action plans [37]. It could show the facility management engineers the state of the climate in each room and occupants wishes. Such UI could be also used by other specialists like building environment professionals to locate places with potential IEQ issues. Standards may arise to govern the process of integrating IEQ with BIM. The following sections present with additional details the effect of different environments on comfort and present a common mathematical model that is used to predict the percentage of thermally comforted individuals.

2.1 Understanding Human Comfort

World Health Organization see health as having full social, mental and physical well-being [49]. This definition suggest that a person who is physically healthy is not necessarily healthy and could be seen as sick without having sufficient mental and social well-being. This definition is complex and hard to quantify as many aspects of mental well-being, for example, cannot be measured with devices. This may suggest that comfort is as a crucial part for achieving better social, mental and physical well-being and being healthy. The study of IEQ cover wide spectrum of domains that affect human comfort.

IEQ is a wide term that incorporate two other terms: indoor climate (IC) and indoor air quality (IAQ). IEQ include a number of measurable factors such as the thermal environment (i.e temperature and humidity), the IAQ (i.e. level of pollution, CO_2 level and the amount of fresh air), the acoustic environment (clarity of sound and absence of noises), actinic environment (i.e. the color and intensity of the light) and the mechanical environment (i.e. ergonomics). In the next sections these terms are going to be discussed briefly.

2.1.1 Thermal Comfort

Thermal comfort yet easier term to comprehend than health is also not easily quantifiable. According to ASHRAE thermal comfort is subjective and is determined by the mind of an individual [47]. Modeling comfort thus, is not merely about installing sensors and expecting that everyone will be thermally comfortable according to sensors reading but also involve assessing the psychological and cultural elements that influence the determination and the perception of feeling which is affected by the surrounding physical environment. Our perception of the outside world is part of the physiology study. The systems that allows a human being to perceive the surrounding are the thermo-regulatory system, respiratory system, eyes and ears. The Core-Skin model divide the body into parts. The inner part represent the core temperature and regulate the temperature at 37°C. The other part represent the temperature of the skin which range between 4°C and 45°C. The lower temperatures occur on the fingers and toes. [28].

The equation that explains the flow of energy and matter between the body and the surrounding is called heat balance equation [29] and is written as follow :

$$H - E_d - E_{sw} - E_{re} - L = K = R + C, \tag{2.1}$$

where:

H	Internal Heat production.
E_d	Heat loss from water vapor.
E_{sw}	Heat loss from evaporation from the surface of the skin.
E_{re}	Latent respiration heat loss.
L	Dry respiration heat loss.
K	Conduction from the skin to the outer surface of the cloth.
R	Radiation heat loss from the outer surface of the cloth.
C	Convection heat loss from the outer surface of the cloth.

The right side of the formula represents the flow of thermal energy from the skin to the environment whereas the left one is the heat flow due to metabolic process.

The rate of metabolism depends on many factors. Among them are sex, age, and diet. This process preserves the functions of body organs and it increases when the amount of cloth decreased. Also, the position of the individual affect the metabolism. The change of position from standing to sitting or to lying change the metabolism rate. In addition to aforementioned, each type of work or activity is associated with different amounts of metabolism. For example, running increase the metabolism in comparison with setting. The metabolic rate (**met**) is defined as the energy produced by a square meter of the human body. The (**met**) for a seated relaxed person is 1 which account for a metabolic rate of 58 W/m^2 [27].

The amount of cloth determines the amount of heat transformed from the body to the surrounding. This amount is determined by the standard ISO 9920 *Estimation of thermal insulation and water vapor resistance of a clothing* for different kinds of clothes. According to *Ergonomics of the thermal environment–Vocabulary and symbols* clothing insulation is the resistance of uniform layer of insulation covering the entire body that has the same effect on sensible heat flow as the actual clothing [38]. **"clo"** unit is used to express the ability of heat conduction for clothes. This unit accounts for 0.155 m^2 ° C/W resistance or insulation. The naked person has 0 clo and in winter it is around 2.5 (clo) when wearing a heavy jacket, padding, gloves and cap. This unit is used to express the relative thermal insulation for different kind of cloths. For indoor daily wear the value of clo range approximately between 0.3 clo (sandals, light socks, shorts, T-shirt, and panties) to 0.95 (Underpants, singlet, shirt, V-neck sweater, socks and shoes) [27].

To model some parameters of the user comfort, it is important to further understand the relevant terms that accounted for it like IEQ, IC, and IAQ. Some factors of IEQ and the metrics and indexes to evaluate them are explained in the next sections.

2.1.1.1 Thermal Comfort Index (PMV/PPD)

Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD) was found by Fanger [29] which use probability to estimate thermal feeling to predict comfort using the subjective judgment to comfort. PMV index evaluates the mean vote for thermal comfort feeling of adults in the indoor environment. The scale of PMV range from -3, which represent cold, to hot +3. These numbers are the output of an equation which takes variables that include temperature, relative humidity, metabolism, clothing as an input in the balance equation. Zero define the state of comfort this is when the subject is not having any thermal discomfort. The predicted percentage of dissatisfied (PPD) is related to PMV. This index estimates statically the percentage of unsatisfied people based on knowing PMV. PPD can also include additional parameters like CO_2 and lighting to estimate discomfort in addition to thermal inputs.

Fanger indices (PMV/PPD) [29] are also used in the Standard ISO 7740. This standard applies to adults of both genders male and females who are in good health in any environment that deviate moderately from neutral condition(PMV equal 0). The purpose of this standard is to predict the local discomfort and thermal sensation. This standard should not be used in very hot or cold environment like kitchens or cold storage.In such cases, other standards should be used. [27].

The equation to calculate PMV is :

$$PMV = [0.303 \cdot e^{(-0.036 \cdot M)} + 0.028] \cdot \{(M - W) - 3.05 \times 10^{-3} \cdot [5733 - 6.99(M - W) - p_a] \\ - 0.42 \cdot [(M - W) - 58.15] - 1.7 \times 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) \\ - 3.96 \times 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (tr + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\}] \quad (2.2)$$

where:

t_{cl}	Clothing surface temperature °C is related to the cloth that the person wear (clo)
M	Metabolic rate (W/m^2)
W	The mechanical power (W/m^2), zero for activities like writing
t_a	Indoor air temperature °C
t_r	Radiant air temperature °C
v_{ar}	Relative air velocity (m/s)
p_a	Partial pressure of water vapor (Pa)

The formula 2.2 shows that most of the inputs are relatively easy to obtain by sensors expect of t_{cl} that require knowledge about the insulation of the cloth and the surface area of the cloth fabric for each person inside the targeted room. Also, the convective heat transfer coefficient should be calculated as it is related to t_{cl}. These values have to be determined accurately in the lab environment. However, for practical applications, it may be sufficient to make an approximation based on individuals answers about the cloth they wear.

PMV is used to obtain PPD from the following formula:

$$PPD = 100 - 95 \cdot exp(-0.03353 \cdot PMV^4 - 0.2179PMV^2 \quad (2.3)$$

The equation 2.3 shows that when PMV is 0, which mean according to the model that the thermal condition is neutral, still there will be 5% who are unsatisfied for varieties of reasons.

2.1.1.2 Local Discomfort and Adaptive Comfort

The setting arrangement in the room varies as some people sit close to the windows others sit close to heater or diffusers. Since PMV and PPD indexes refer to the average condition, relying on PMV and PPD alone is not sufficient in determining local comfort.

Among the causes of local discomfort are:

- The presence of drafts caused by air infiltration from opened windows and doors and from windows frames
- The radiant temperatures asymmetry which makes the person feel, for example, cold from the left side of the body and hot from the right side of the body. This mainly related to the differences in temperatures between roof, floor, and walls.
- The temperature of the floor which relate to the material that is used, insulation and the type of footwear.
- The differences in air temperature as sensed from the floor up to the roof which could be caused by improper insulation for the floor or the ceiling. The percentage of dissatisfied due to this can be estimated.

The feeling of discomfort can be mitigated by giving the occupants some control over their environment. It was found that people try to adapt to restore the state of comfort when they are subjected to uncomfortable indoor weather [46] .Occupants can adapt to the environment, which is not necessarily found neutral by PMV, by many forms of adaptation:

- Behavioral: like opening windows, turning the fan on/off, remove or add some clothes or moving or dancing instead of sitting
- Physiological: by getting used to the indoor climate
- Psychological: this is different from physiological as in the physiological the body adapt but in psychological, even the thermal parameters are not satisfactory, the individual tolerate it.

The ability to adapt is influenced by many factors like the dimensions of the space, the colors used and the presence of plants. Having windows, curtains, mobile heater, accessible personal thermostat, not wearing a uniform all helps in achieving adaptive comfort which help in controlling operating temperatures, according to the season, and saving energy.

ASHRAE Standards 55-2014 and ISO 7730 are among the references that can be used to determine the comfort including adaptive comfort by diagrams that take into consideration many of the studies that were made in this field. Also, many software are developed and used by architects and engineers who are interested, more than ever, in designing sustainable buildings. Ladybug tools are one of those which are open source and available free of charge uses Rhino and Visual Programming language like Grasshopper and Dynamo in addition to Python scripting. They consist of mainly of four packages Ladybug for preliminary analysis of design options and the potential of saving by having passive energy systems and lighting, Butterfly is used for CFD simulation, Honeybee for energy modeling and Dragonfly for urban studies and projections. The tools help Architects and Engineers designing buildings and neighborhoods that adhere to sustainable development guidelines of maximizing comfort with minimal energy consumption. Ladybug tool (`http://www.ladybug.tools`) integrate some of the standards like ASHRAE Standards 55-2014 in addition to other standards and references to provide, among other features, interactive climate charts that visualize the results in 2D and 3D models using Energy Plus (`https://energyplus.net/`) climate data files and simulate energy consumption during the years. It can help to analyze and answer many questions related to thermal comfort and predict the number of hours with achievable comfort, using passive HVAC strategies, without depending on active HVAC system (achievable only if the building is designed properly). For example, figure 2.1 show on the psychometric chart the number of hours that are expected to be thermally comfortable/uncomfortable for a particular condition throughout the year for a city in LA,USA.

The dark black polygons represent the condition of comfort, i.e. the condition is considered comfortable if it occurs inside the polygon. Adding measures that increase the adaptive comfort potential extend the area of the polygon region and increase the percentage of time where comfort can be achieved passively. The red color on the psychometric graph represents more hours and the blue fewer hours. If the red, many hours of thermally uncomfortable state, occur out of the comfort zone, then some strategies have to be implemented to maximize the hours of comfort (moving the red spots to inside the polygons). Ladybug has a component that accounts for a different kind of adaptive comfort like having the ability to change cloth or having

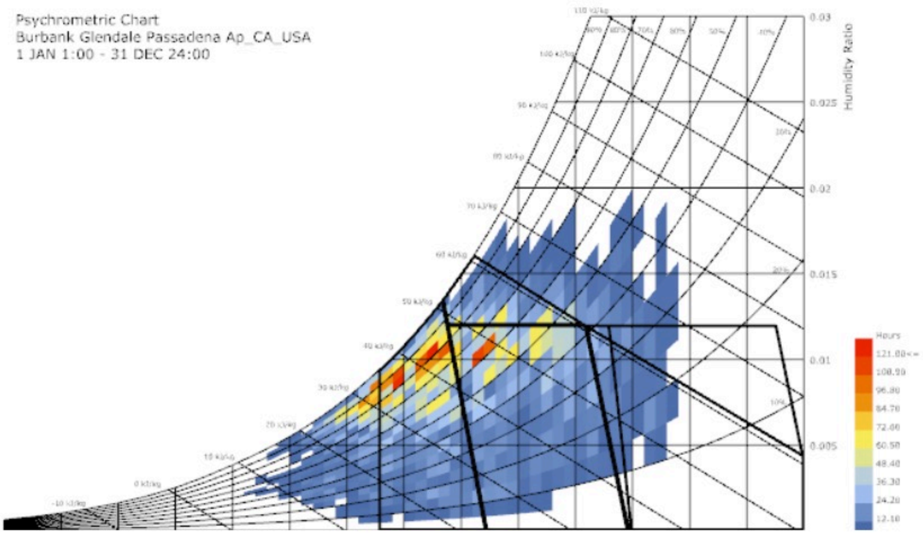


Figure 2.1: Ladybug visualization for 1 year conditions without using HVAC system

access to the window to estimate how these mitigate the hours of discomfort conditions. It can answer questions like how the percentage of discomfort will increase throughout the year if the occupants have the ability to open/close the windows? What is the increase of percentage comfortable if they can adjust their clothing? What about combining all possible aspects that account for adaptive comfort, how much gain in comfort percentage? Figure 2.2 illustrate this idea and show visualization in 2D for such questions. The vertical axis represent the time of the day and the horizontal axis represents the days in the year. The red zones show the time and the day when it is possible to achieve comfort level passively, without active HVAC systems, by activating the potential for achieving adaptive comfort outcome.

Each graph above shows the comfort resulted from applying particular measure or strategy to activate the adaptive comfort. The first graph strategy is to allow for changing cloth, the second for evaporative cooling, the third by applying thermal mass and night vent and the last graph for internal heat gain consequently. For the city presented here there is a huge potential of increasing the comfort due to heat internal gain through out the year. The graphs also show the effectiveness of each strategy throughout the year, for example, evaporative cooling can be effective for some hours during the end of April also for sometime during August and September.

Ladybug tools with other open source tools give a comprehensive solu-

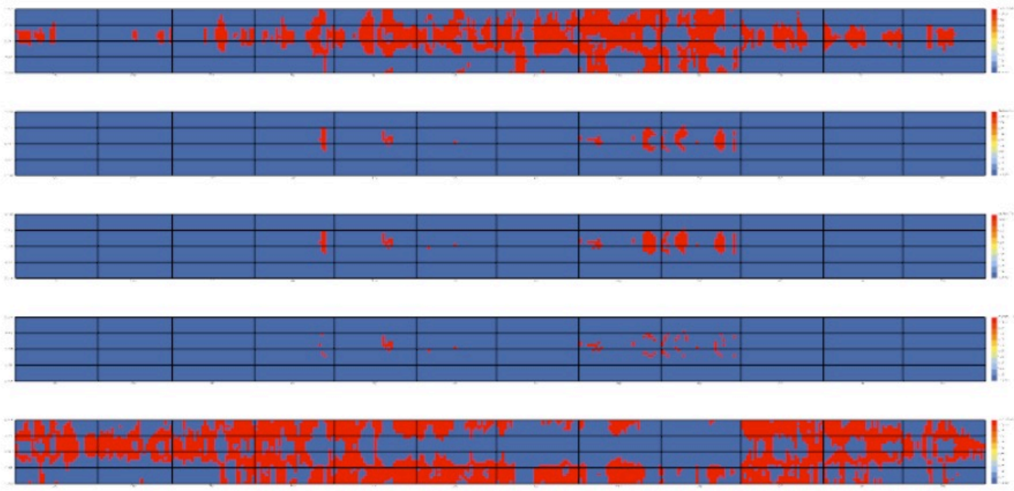


Figure 2.2: Comfort (red) that is achieved by using five different passive technique
Source: http://www.ladybug.tools/

tion that relies on technical, design, engineering and programming skills to modernize the process of sustainable design that maximizes comfort using interactive platforms (Grasshopper with Rhino). Figure 2.3 shows how the open source tools talk with each other and relate to each other to facilitate better designs that are more environmentally friendly.

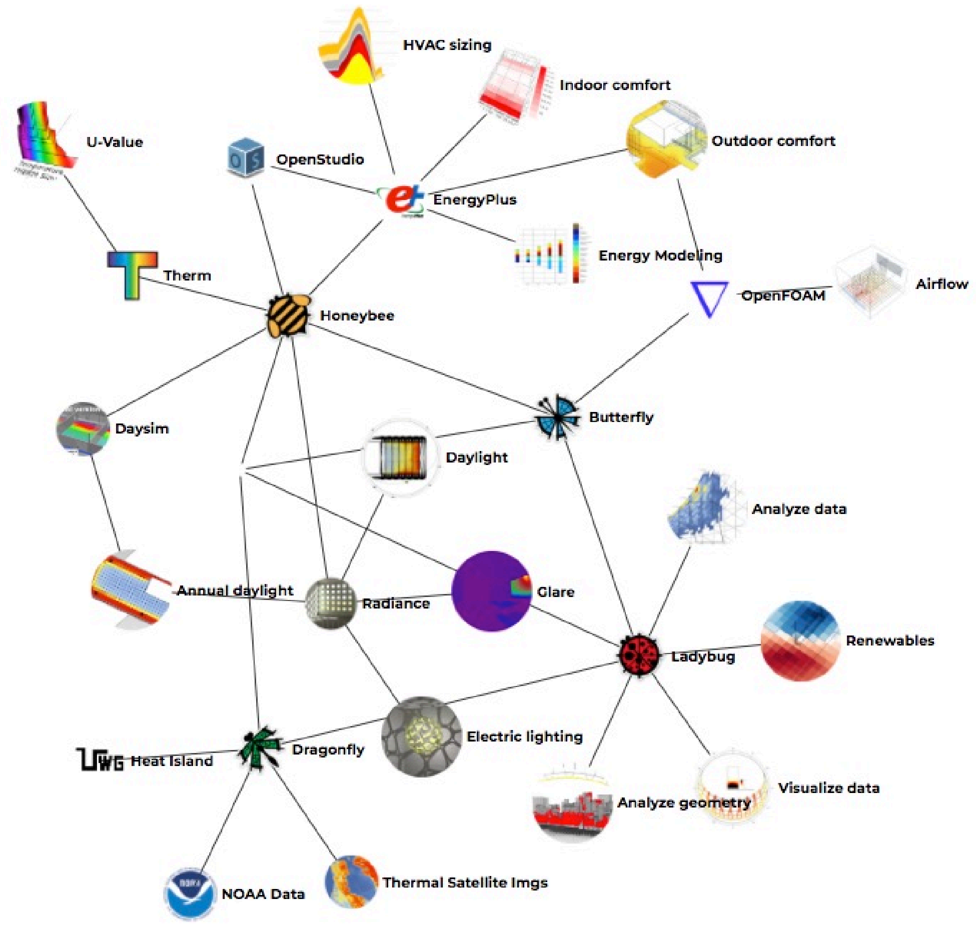


Figure 2.3: Ladybug and other related open-source tools used to help in sustainable building design
Source: http://www.ladybug.tools/

The above figure dismantles the complex world of creating comfort into many areas of studies like air flow study using Butterfly and OpenFOAM, daylight using Daysim, insulation study (the envelope of the building) using Therm. The beauty of it that it shows the mosaic of design and engineering knowledge that are harmonized to create a sustainable building with maximized comfort. Yet still, this representation of comfort miss many other physical factors that account for comfort like IAQ.

2.1.2 Indoor Air Quality

Many diseases, health issues, and discomforts could be caused by improper IAQ. According to WHO, approximately 20% of buildings occupant suffer from (SBS) which include symptoms like dryness of nasal and asthma. The dryness also occurs to the eyes in addition to irritation. The individual with (SBS) may also suffer numbness, problems in concentration and drowsiness. It is expected that SBS is related to the level of ventilation, pollution, lighting, sound, noise, psychology and physiology of the individual among other possible factors that may cause it. Human sensors trigger warning about improper IAQ that may cause sore eyes, headache, and diseases. IAQ can be assessed by sensors and also by subjective evaluation. The subjective assessment of IAQ is important because pollutants come from different sources and it is complex and challenging to know all types of different pollutants in the space, like smoke, chemical emissions, and biological aerosols, and then expect the level of dissatisfaction.

ASHRAE Standard 62.1-2013 is used by engineers to determine the requirements for room ventilation and set the acceptable IAQ. This state does not mean that pollutants do not exist in the space, but rather the state at which there is no harmful concentration of pollutants that may cause contamination and dissatisfaction to at least 80% of people. The standard also gives recommendation related to equipment installation, maintenance, operation and commissioning because the situation of HVAC system affects the IAQ. [16].

The pollutants that affect the IAQ are classified into three main categories chemical, physical and microbiological. Among the chemical pollutants are ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon dioxide(CO_2), carbon monoxide(CO), tobacco smoke, pesticides and volatile organic compound (VOC). The physical pollutants include radon, asbestos, man-made mineral fibers and dust.Pollutants like viruses, bacteria, mold, fungi, mites, and pollen are classified under the microbiological pollutants. The pollutants can be generated from different sources.Some outdoor pollutants are dust, ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and pollen. The indoor pollutants are generated by humans which expressed using "olf" unit, the pollution that is produced by one person at metabolism rate of 1.2met under standard thermal comfort and standard hygiene of 0.7 bathroom/day. Humans also generate carbon dioxide(CO_2), bacterias, viruses, and tobacco smokes, dust and VOCs. Combustion and food cooking generate gases like NO_x, Carbon monoxide CO, Carbon dioxide CO_2 can all be generated indoor. Different kind of particles of known and unknown nature classified according to their sizes under two main categories ($PM_{2.5}$) and

(PM_{10}). Formaldehyde (HCHO) is generated by some type of furniture and insulation panels. Deodorant, cosmetics, stain remover and detergents are all sources of pollutants. Some machines that are used indoor like printers and photocopiers generate pollutants such as ozone (O_3). Lead (Pb) is also among the pollutants that exist in paint. The HVAC system malfunction could be also a source of dust, fibers, mud, viruses, and bacteria. The materials that are used in construction like gypsum, clay, asbestos emit different kind of pollutants to the air. Some of the pollutants, at particular concentrations, can be sensed by humans especially those which have a bad smell like human odors measured in (olf) and (O_3. However, some other which are dangerous and increase the probability of cancer like Radon (Ra) [21] are not detectable by humans olfactory as it is orderless, tasteless and colorless [25]. Indirect perception of pollutants could be possible when particular symptoms appear on the person like the feeling of tiredness that is caused by Carbon dioxide CO_2. WHO is among the bodies that set standards to determine the allowed concentration of pollutants and the time of exposure for each concentration.

2.1.3 Other Factors That Affect Comfort

In addition to IAQ and thermal comfort, there are many other physical factors that account for comfort like lighting intensity inside the space, the color of lighting, the source of lighting and how the intensity and the color change during the day [58] [36].

The acoustics is also important in the perception of IAQ. The noise, which could be comprehended as unwanted signals, is a form of pollution. Today, it is doubled in the cities (measured in dB) in comparison with what it was 20 years ago. The possible consequences are negative effects on health and symptoms that include irritability, the rise of blood pressure, problems with concentration, decreased working capacity, fatigue and avoiding communicating with others. Moreover, some blame it on the noise that some humans became more hostile as even moderate noise level reduce the tendency to offer help for others, raise the anxiety and the probability of hostile behavior. Additional symptoms are found in occupations that have a high level of noise including increased level of adrenaline and cortisol, gastric problems, stomach ulcers and stress. It is estimated that the EU losses between 13 to 38 billions as environmental damage due to noise. [57]

Some other factors like ergonomics of the space, the type of furniture, the colors, setting arrangement, visual privacy, the shape of the space, the spaciousness, type of materials, the existence of windows among many other factors play a role in the subjective perception of comfort and IEQ.

2.2 Using Questionnaires to Assess Subjective Comfort

Fanger experiment to model the comfort was performed in a laboratory which controls the variables and the subjects. Later studies from other authors have confirmed the findings of Fanger inside a controlled environment. Later studies from other authors have confirmed the findings of Fanger inside a controlled environment [29]. But since Fanger model is developed many years ago, it is probably logical to address the subjective comfort using modern technologies like IoT and real-time mobile application out of the laboratory environment by getting direct inputs from occupants.

The subjective judgment for the thermal environment is defined by Standard ISO 10551 as an assessment which uses subjective scale [32]. In such kind of assessments, consideration for the outdoor condition and the type of clothing and clothing adjustment (are they forced to wear a uniform or not) should be made. This method may include some objective results that could be compared with the measurements and then perform statistical analysis to find relevant correlations, build knowledge and form a new hypothesis.The purpose of the questionnaires could include evaluating the ergonomics of the space, widen the understanding of the relationship between humans and the environment and welfare, modify the environment or human behavior. The importance of such studies is to show a correlation between the physical data, that cannot express humans feelings and needs, with the humans judgments. The judgment about the perceived or desired conditions, could be local in the room or involve the whole building. Also, the assessment may be at the moment, extend for some hours or a whole day or a season. It can ask about the present or the past and if it asked about the past then the researcher should be aware that asking about historical data may cause bias in answers as people tend to forget and this increase the uncertainty in answers. Questionnaires, in addition to comfort modeling software that were explained earlier, can be used together to assess and predict the feeling of comfort considering the aspects that influence the subjective feeling of comfort. Users of the building have a perception of comfort not only related to psychological aspects but extend to domains, social and cultural, that are particular and different among individuals. The fact that this is an international standard, give validity to using subjective methods for assessing comfort level. This standard can be used to evaluate IAQ, light in addition to thermal comfort. The use of questionnaires is regarded as an empirical assessment to understand the real state of comfort as perceived by senses thus it is considered an acceptable approach [27].

The judgment according to Ergonomics of the Thermal Environment: Assessment of the Influence of the Thermal Environment Using Subjective Judgment Scales *should evaluate or make an assessment of the current condition* [32]. This can be applied to any aspect of the environment from lighting to sound to temperature. The assessment mean that the respondent assess the environment by saying it is hot or cold. The other type of judgment is perception where the respondent rate how good or bad the experience is. The last type of judgment, defined by the aforementioned standard, is "preference" where the respondents tell what they prefer.

After collecting the answers of IEQ or thermal comfort, a statistical analysis to find value from these responses can be made. The answers might not be accurate for all participants especially for uncertain individuals. [27].The analysis of the results could be done using one of the following technique:

- Probabilistic technique which calculates the statistical error. Can be used when the list of respondents is known.
- Non-probabilistic technique which does not calculate the statistical error. This method can be used when the population of the study sample is unknown, in a pilot survey or exploratory type and when the budget is low.

2.3 Gamification of Surveys

Today, participants in surveys are more expecting to get some kind of positive return for the time that they have to spend filling, mostly, boring and uninteresting questions. The user experience (UX), that is now taught as a graduate specialization in universities, main goal is to create better usage experience for people by studying their behavior. In software and interactive digital content, UX include usability, novelty, and involvement. According to Callegaro et al. [18] none of the UX goals are widely applied to survey questions. The visual interactive content increases the level of satisfaction but not necessarily the level of engagement. Some types of questions reduce engagement like using tables and open questions. Users who do not feel engaged may be more prone to errors and giving irrelevant answers. [18].

The main reason for using gamification in the survey is to add features of games to other areas and to ensure engagement. It was found that gamification affect users positively psychologically (feeling happier) and behaviorally (feeling motivated to participate). This means that the user will not only have the impulse to try or start the surveys but also get mentally stimulated to continue participating. The user should not only feel engaged but preferably in the state of flow which defined as being completely focused. This adds fun and reduce the errors according to some recent studies. The increase in the interactivity of surveys can be furnished by providing slide bar instead of multichoices radio buttons or checkboxes. More advanced level of interaction can be provided by using pictures and progress bar. Such kind of incentives for participation may be easier to have inside games and surveys. However, high-end gaming elements like badges, stories, points, that demand programming knowledge, rarely appear in surveys. Technique like personalization and role-playing further increase involvement. Gamification should not be confused with surveytainment. The second provides appealing fun content like awesome graphics, interactivity which share some elements of gamification but is narrower term than gamification as it focuses mainly on web surveys that is, probably, more cognitively demanding [18].

Empirical deep studies about the advantages of using games in surveying is limited. However, it was found that using visual and interactive elements like avatar, virtual reality (VR), awards and stories among other games elements produced high quality results, richer responses and more satisfaction level and sometimes more response rates. [18].

Long questionnaires have a negative impact on participants and it was shown that it causes fatigue. Respondents can express their annoyance by quitting or by giving inaccurate responses. [18]. It was also found that questions that are less cognitively demanding are better questions. This means that long question that is less cognitively demanding is better than a short one that is cognitively demanding. [18].

Considering that the attention span of a human is around 20 minutes, one can conclude that short and cognitively undemanding questions are expected to increase engagement in comparison to long and cognitively undemanding. The break off from participating increase as the questions get longer. Also, culture has to be taken into consideration. People from Japan prefer shorter questions in comparison with people from South America. [18].

2.4 BIM Integration

Throughout the last years, the adoption of BIM has been rising as the advantages of BIM implementation has become more evident at different stages of project life cycle [17]. A simple search on Google Scholar shows that there are more than 2700 scientific articles about BIM which have been written in the first four months of the year 2018 alone. During the last few years, the number of construction firms that advanced from the usage of conventional

CAD drafting to BIM, mainly in the design stage, has seen a rise. Standardization of the 3D models, with standards like IFC and gbXML, made exchanging the information across different platforms and software possible, but not yet ideal. BIM has started to become the norm and other conventional way, like drafting with CAD software, is expected to gradually retire. BIM share in the market is expected to increase continuously at the expense of other traditional technologies and work procedure associated with, old yet still widely spread, drafting tools that linked with a particular set of softwares like AutoCAD.

Some of the reasons for the shifting into BIM can be summarized in minimizing different forms of wastes that are originated from many sources. The most common types of wastes are in time, money and manpower. Such wastes are broadly analyzed in the scientific community in more detail to find the underlying causes and explore possible solutions to reduce them to further focus on improving the quality. Thus, many projects owners, designers, and engineers are demanding the usage of BIM in their projects.

The application of BIM in design and project management has been implemented for many purposes and scopes to gain varieties of profits. The scope of BIM applications varies among disciplines and phases. Visualization of the 3D model in what could be called virtual modeling of the geometry and the information parametrically is strongly connected with the BIM term. In addition to this, BIM is used in scheduling, cost estimation and quantity takeoff. Many advantages of using BIM in this field were documented in the literature. On-site management of wastes during the construction phase and during demolition and renovation [20, 42] represent some of many examples. Relying on BIM for scheduling and budgeting the project facilitates the organization of the work procedures and processes during its life cycle. The impact of a change order on the budget and schedule is easier to comprehend and estimate by updating the changes to the model with the new data and designs. Better communication can be achieved between different stockholder due to this. Changes in designs and their impact on schedule and budget can be seen directly. Actually, by adopting BIM at early phases of design, the number of RFI (Request for Information) and change orders can be minimized. BIM also provides fast means to access a different kind of information like warranties, specification and maintenance. All of the aforementioned are expected to raise the overall satisfaction of the project owner and their representatives. [17]. This should reflect on savings in time, money and manpower and allocate more time in developing the other aspects of the business and on quality optimization.

The implementation of BIM in construction project management represent only one of BIM applications that are developing and modernizing rapidly. This is by all means only a fraction of the fields or domains that utilize the broad potential of information modeling/management. The potential of extending the application of BIM into more sectors is heavily researched during the last years. Benefits are continuously arising in new systems or application such as in medicine, traffic control, economy, image processing, manufacturing, forecasting and social science [52].

Virtual Design Construction (VDC) was found to advance learning, prepare students for a job in an industry and increase engagement [40]. Chen et al. [19] visualized the coverage of closed-circuit television (CCTV) in public building relying on BIM technologies for traffic management. Noise level was mapped to the 3D model by Cheng and Anumba [22] using BIM to assess the noise level at different places. In education, BIM is used to teach sustainable design, i.e Ladybug tools, and the effect of design on energy performance by integrating information like reflectivity, transparency, thermal resistance, climate data and other properties within the geometry. This kind of education is tested and showed good results, incorporating project based learning (PBL), achieved using Autodesk Ecotect and Revit [56]. The retrieval of information via image processing from 2D images to construct the 3D model and laser scanning to construct as built model is performed by some researchers [33, 41]. BIM can also be used in the application of predicting and forecasting the future. For example, using a 3D model of a city with BIM can help in forecasting the future needed energy for the urban. Pazhoohesh et al. [51] explore using computational fluid dynamic (CFD) and BIM, to locate individuals in spots that minimize energy consumption and maximize thermal comfort with automatic control of lighting and air conditioning. The previous examples show some samples of BIM applications that are widening across industries. However, the usage of BIM to model human behavior and preferences is new and not widely researched. The next section explains further some of the work that has been done.

2.4.1 User Behavior, IEQ, and BIM Integration

The new regulations that concern today's and future buildings will continue to be stricter and will demand reduction in energy consumption and the adoption of sustainable measures. The emphasize to achieve this in buildings can be classified into different areas:

- Energy: Modernizing the HVAC systems and exploit renewable energy
- Architecture: Modernizing the built environment to be healthier, i.e use eco-friendly materials, passive lighting and harmonize with the surrounding, and rely less on active HVAC systems

- Individuals: Understand and alter the behavior of occupants and optimize the built environment to suit their comfort with minimal energy consumption
- Resources: Reduce wastes by utilizing on-site water and recycle wastes

The previous sections explained the essential role of BIM in achieving many of the previous goals. This explain the rise in studies concerning IEQ and BIM integration. However, many of the studies today focus on the objective comfort and energy performance parameter that influence IEQ. For example, Marzouk et al. [43] were able to apply an algorithm, with weights to different factors, to prioritize the maintenance of subway stations that have deterioration in their IEQ. Better ventilation level and thermal comfort were achieved and the amount of particulate matter (PM) entering the subway was lowered.

User behavior governs the amount of possible savings that can be made. As the user becomes more responsible and following sustainable practices, the potential for saving, achieving more energy efficient building performance and comfort may increase. Thus the importance of user input cannot be underestimated. Users of the buildings represent the social system inside the building that judges the physical parameters and influence building operations economy.

Users responsible smart behavior could be assessed by their level of satisfaction about IEQ that involve, as mentioned previously, factors like the subjective evaluation of the beauty of the building, cleanness, IAQ and thermal parameters. It is expected that comfort can be maximized by making the occupants aware of the building different parameters, like the temperature in the room, the lighting, RH level and other parameters. This could be achieved with the help of sensors that integrate with ICT. Occupants can perceive the state of different parameters that are fed by sensors to their devices. Also, they can participate in sending their preferred indoor environment parameters. The smart users should be engaged in using ICT technologies, i.e with gamification features, to educate themselves further, learn about the best practices and understand other occupants preferences comparing to their own. The smart building that is used by smart users should have instant way to establish communications via fast channels, i.e chat service, to have instant access for support, guidance and help.

A framework for improving IEQ in education premises was piloted [15]. Mainly three parameters were tracked, assessed and integrated with BIM which are thermal, IAQ and visual/lighting comfort which claimed to be an important asset for the management to maximize health and the performance of students.

2.5 User Centered Design (UCD) and Usability

Many reasons make a product hard to use among them is that the focus is put mainly on machine or system during development without involving humans.The other reasons are the changes of people needs, the improper integration of work between team members and the variation between the design and implementation. Also, it should be noted that designing usable products is a difficult process. Design for usability is the fruit of multidisciplinary teamwork with expertise not only in engineering but also in art and social science. The preliminary product can be evaluated by users, as users judgment give the most credible evaluation of usability. [53].

The process of user-centered design has a repetitive iterating nature. The focus of development is on the user uses to build a product that meets what the development team thinks about the user needs. Then the product usage gets evaluated and the outcomes and finding are fed to alter the design. The design should involve the users from an early stage. [53].

There are many techniques to build proper understanding about usability. Ethnographic research which intends to watch the users closely and document how they potentially interact with systems in the place where they are expected to use it then develop a persona and task descriptions. Part of the development team can also act as the intended users and guide the development in what is called participatory designs. This may lead to biased results as people from the same team may tend to agree with each other. Focus group is a small group where the team can work with closely to evaluate users opinions in depth about the preliminary concepts in different forms such as storyboards and hand drawings. This gives qualitative information about how the user thinks and feel. The result however, does not reflect what the user will actually do as users are saying what they think they will do. Some other method of understanding usability like survey can also be used. The main feature of the survey is that it can reach wide sect of people but it is not expected to produce as thoughtful responses as group review. The developer can organize a walk-through session to tell the user how to use the application and record the difficulties and comments. Specialists in UX and UI who have studied human factors and who preferably also specialist in the subject of the application (i.e IEQ specialist). After all of the previous methods, usability testing should be conducted. The usability testing either start from a hypothesis that gets validation by the test or can be seen as an iterative cycle of tests. After releasing the product follow up tests, which is the most accurate form of testing, should follow. [53].

Chapter 3

Environment

3.1 Aalto University

Preserving an acceptable quality of the indoor environment is important for health and comfort. In public premises, the high density of people strengthens the importance of meeting occupants needs and preferences. Students spend a long time of their time in education facilities. Their performance and productivity is correlated to IEQ. U.S General Accounting Office has found that the educational buildings have relatively more probability to have deficiency in indoor environment due to limited funding and lousy maintenance schedules [48]. IEQ contribute in improving the learning outcome and performance in schools [30]. Lee et al. [39] compared the subjective inputs made by occupants and objective inputs from sensors to evaluate the IEQ and its relationship and impact on learning in universities and found strong correlations between IEQ and student performance. A review of more than 30 articles that studied the impact of HVAC systems characteristics, pollutants and thermal condition on the performance and health of occupants in different buildings also confirms that deterioration in IEQ impact learning performance [44]. Due to the aforementioned factors, I have chosen to make this case study in Aalto classrooms.

3.1.1 Otaniemi Buildings and Classrooms

Many of the buildings at Aalto University, Otaniemi, were built tens of years ago. Most of these buildings have shapes that are made by combining rectangles and their height varies, mostly between 3 to 5 floors. The external cladding is made with brown bricks figure 3.1.

New buildings were also constructed during the last years and some other are under construction. Those seem to be more spacious and seems to use

Figure 3.1: Otaniemi during summer/autumn
Source: http://arts.aalto.fi/fi/campuses/otaniemi/

more eco-friendly materials figure 3.3. In many of the old buildings the heat-

Figure 3.2: Computer Science, relatively, new building
Source: https://www.flickr.com/photos/stefankoegl/4982323984

ing is provided by an active heating system using radiators. The ventilation system seems to utilize the stack effect concept mostly through air ducts. Ducted air supply system is not widely implemented in the classrooms.

The characteristics of the classrooms vary inside each building and also between buildings and schools. The sitting arrangement and the areas of the classrooms are different. Some have colorful movable furniture that promote interaction. These are suitable for group work, classes that involve discussion or courses with active teaching methodologies. Lectures do also take place in conventional large classrooms/halls with a high roof.

In general, artwork and indoor plants are rare inside classrooms. The color or the walls are mostly white. Many classrooms have transparent double glass windows that could be opened manually and some that face outside of the building with possibility to adjust the shading on them. The lights are mostly fluorescent white lights, figure 3.1 show a room in Otaniemi.

Figure 3.3: A room in Otaniemi
Source: http://facilityrental.aalto.fi/en/otaniemi/

Chapter 4

Methods

4.1 The Proposed System

Based on the previous chapters, a diagram was made to illustrate the principle of the proposed system explained in figure 4.1.

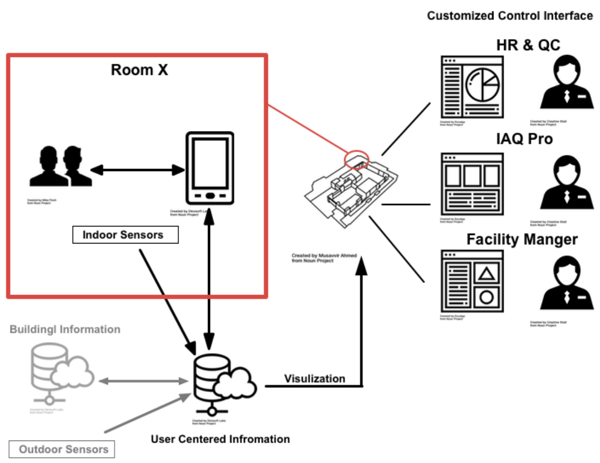


Figure 4.1: The proposed concept

As shown in figure 4.1, the system has a central database that stores real-time data about some objective parameters that are obtained from the sensors in addition to the subjective ones that are inputted to the system by users. Each room in the building should have a set of sensors that measure some parameters like lighting, acoustics, temperature, humidity, and pressure. Also, the measurement may include elements that form health risk at particular concentrations such as Radon (Ra), CO_2, SO_x, NO_x, particles like ($PM_{2.5}$ and PM_5) and also VOCs.

The system is personalized for each individual according to the room they visit and the lectures/courses they have. The user interacts with the system via their devices like mobile phones or desktops. The user can receive information for example about the sensors readings or the average of other occupants opinions. Also, information can be directly exchanged with the relevant parties.

User exchange data and sensors send data to central cloud-based database. This database can communicate with other platforms and receive data from other databases. For example, it can communicate with BIMserver to get information about the IFC model, like the location of the room or the geometry of the room or the ratio of windows to wall inside the room, to further assess the data that are coming from users in relation to other information about the building and its rooms. The main purpose of the user-centered database is to relate the gathered information with each user. In other words, the collected data is personalized according to each user, their location and time in the building. The part shown in gray ,is important for future development of the proposed platform, yet it is out of the scope of this thesis. The user should perceive this platform and the main and central channel to report matters related to their well-being and the environmental quality.

The user centered-data are shown with real-time visualization on the 3D model in the place where it was occurred. The visualization should give instant understanding for the state of the different parameters in the building. The abundance of properly presented and visualized information form the asset to develop customized interfaces that suites the requirements of different professionals to assist them in decision-making process and judgment. The interface also should facilitate direct communication between occupants and other professionals in management like IAQ professionals when symptoms that could be related to indoor air quality arise.

Some guidelines for the proposed system is summarized as follow:

- Has modern, simple, clear and user-friendly and mobile friendly interface
- Has a central database that stores inputs from users and from sensors
- Promote user engagement by using gamification
- Make the user aware of the parameters of indoor environment in each room.
- Act as the main ranking and evaluation systems for building IEQ.

- Used by users as the main system to get help in cases related to IAQ symptoms and other needs related to the indoor environment
- Visualize the data in real-time as part of BIM
- Has an evolutionary content that is centered around understanding user behavior, preferences, and comfort.
- Require minimal input from occupants
- Feasible to interface with other software like energy modeling and daylight simulation for the potential to form an integrated system that optimizes building performance (this is out of the scope of this thesis).

The next sections discuss in further details the requirements of the proposed systems

4.2 Designing the Application

4.2.1 Determining the Main Features

Before implementing the system, a prototype user interface (UI) was designed using Marvel Application website `https://marvelapp.com`. The first UI concept adheres to keeping the UI simple and minimal but it did not meet the gamification goals that were discussed in chapter 2. Figure 4.2 shows the first design attempt which shows one of many questions that are expected to be answered by the users. The system should periodically send a set of questions to the user and the user have an option to skip any question. Some of the questions included images to illustrate them.

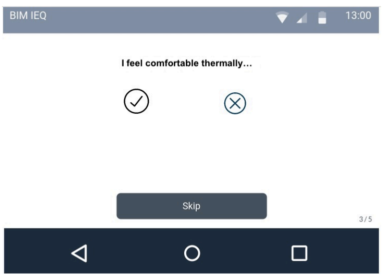


Figure 4.2: The first design concept for the interface

This way of questioning may not be appealing to the user and does not comply with gamification concepts. The process of questioning/surveying could be boring and does not give the user any value. The assumption was that seeing the average rating that is made by other users for different rooms as shown in figure 4.3 may lure the user to participate.

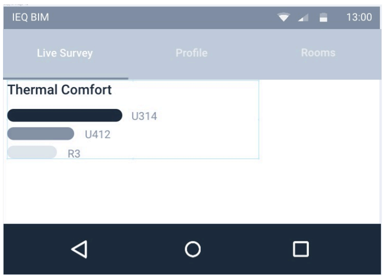


Figure 4.3: The proposed concept

Figure 4.3 graphs show that the user has selected particular rooms and thus the interface is personalized to show the user the thermal comfort in these rooms based on the answers to set of questions that were shown in 4.2.

The UI and user interaction concept was redesigned to comply with gamification concept and to attempt to make the platform more interesting for the user. The updated concept allocate a logo to the system that is inspired by Aalto logo as shown in figure 4.4.

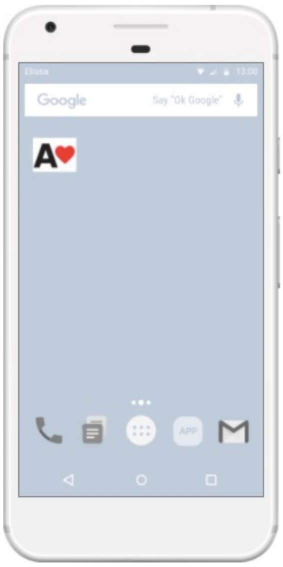


Figure 4.4: Application icon inspired by Aalto logo

This web application is correlated with comfort, quality control and well-being thus the heart beside the letter ”A” that represent Aalto name. However, the main logo was changed later to match the domain name and the story that is part of the gamification. More detail about this will be explained in the implementation section.

The importance of having proper logo and branding should not be underestimated. According to Airey [14], the identity is an essential part of any created service to attach value to it. People, in general, do not necessarily spend their money for the actual value of a product but rather for the perceived value. The logo should be simple, relevant, enduring, distinctive, memorable and adaptable. Also, the author emphasizes on simplicity and clarity when designing a new logo. [14].

When the user clicks on the icon, s/he log in and then select the rooms/lectures that are relevant to them. After this, the dashboard or the main screen appear as shown in figure 4.8.

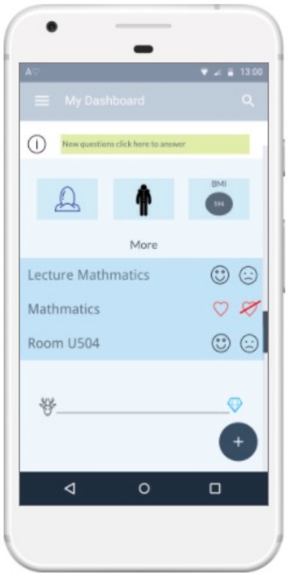


Figure 4.5: Concept application design - the home-screen

This screen in figure 4.8 shows that the user has interacted with two content and gained two badges (icon of a man and the gray circle on the right of the black man icon).Both of these badges give a ranking for the user and compare the body mass index (BMI) of the user with other users as shown in figure 4.7.

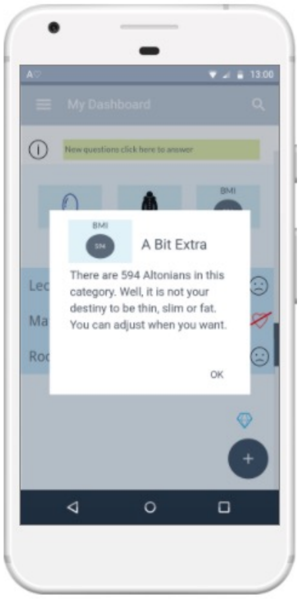


Figure 4.6: Concept application design - BMI badge

The level of the user is "unhatched egg" as the participation of this user is still low and the user has lectures in room "U504" and has "Mathematics" course. When the user clicks on the badge a pop-up screen appear 4.7. The user can rate room "U504" environment by tapping/clicking on the happy face if the user like the room and the sad face if not. The selected face change color when tapped. The same applies for the course, clicking on the happy face means that the user thinks that the course is good. The interface also has the possibility to rate if the user like/hates the subject "Mathematics". The screen shows that the current user did not collect enough points to reach the next level. The box in green shows that there is a new content that requires user interaction. The user can collect more points by rating the rooms, subjects, and courses or by using the interactive content or by submitting their preferences about temperature and lighting. As the user gains more points the head of the reindeer move toward a prize.

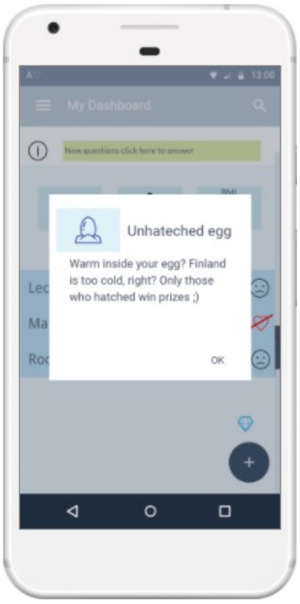


Figure 4.7: Concept application design - first badge

When the user clicks on "Room U504", a screen shown in figure 4.8 appear. It shows the level of overall satisfaction/dissatisfaction about room "U504" indoor environment for the users of the room, current temperature, RH% and lighting in the current room "U504". Tapping on one of the cards

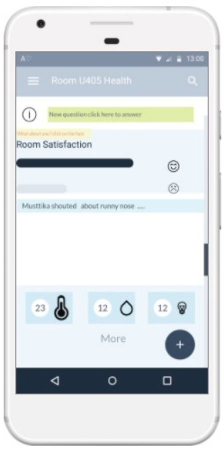


Figure 4.8: Concept application design - room screen

will show the screen in figure 4.9. The user can see the average preferred temperature in this room and also set their preference. User also can set relative humidity preferences and lighting.

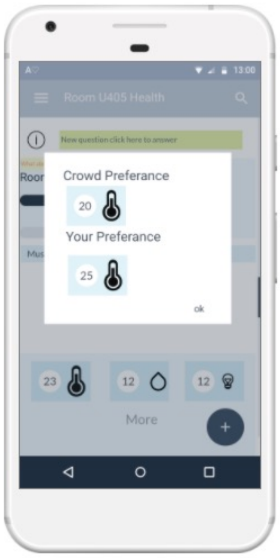


Figure 4.9: Concept application design - average preferences for temperature

This summarises the main features of the application.The next section explains briefly the design of the UI.

4.2.2 Designing the User Interface

The design of the UI was inspired mainly by Material Design guidelines `https://material.io/guidelines/`. This is a design language that is developed by Google in 2014 and then adopted by Google products such as Android applications like Gmail and Youtube [45]. The philosophy of it that the principles of good design could be applied to science and technology innovations. The goal is to unify users experience across platforms, considering the variety of devices sizes and input methods.

Material Design has a design philosophy that may interest user interaction specialists (UX) and artists, which is out of the scope of this work. The selected colors followed the guideline of using primary and accent colors. The primary colors, for the red color as an example, are numbered with numbers like 50, 100, 200 till 900. As the number increases the tone of the color increase. Google suggest using the number 500 as the primary color for the user interface and this guidance was considered. Primary color are the colors that appear frequently in the application. The accent colors have the prefix "A" in front of them and have the numbers A100, A200, A400, and A700. Secondary colors are accent colors that highlight particular keys or buttons in the application. Figure 4.10 shows the numbered tones for primary colors and accent colors.

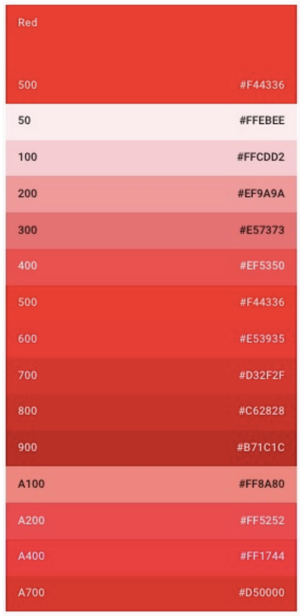


Figure 4.10: Material design - red color primary and secondary tones

Chapter 5

Implementation

This chapter explains the solutions that are used to achieve the outcomes that are mentioned in the previous chapter. The solutions include the selection of ICT and sensors. The final implementation of UI and features of the application will be further explained in this chapter. The final section explain the methods that are used in testing the concepts.

5.1 Software Solutions

The features of the final application and the required user interactions governed the selection of the technologies. The plan is to build a prototype concept rapidly using the technologies that I have some level of familiarity with. One of the required features in the software is to have a real-time system that can visualize the required parameters as they occur. The first consideration of back-end framework technologies selections was centered around Django, Flask or a framework that use Node.js. Django and Flask both are web frameworks that use Python programming language for backend server programming (`http://djangoproject.com`) whereas other frameworks that are written with Node.js use JavaScript (`https://nodejs.org/en/`). JavaScript is used commonly to program the fronted, this is the same language that is used by frameworks that uses Node.js to program the backend. Using Python framework gives access to strong specialized libraries that are not otherwise available for JavaScript like SciPy. Also, Python syntax seems to be more human-friendly than JavaScript, a factor that may account for increased productivity.

Stack Overflow is a website used mainly by developers, software engineers and programmers to ask and answer questions related to information technology (IT). As of April 2014, there are 4 million registered users and more than ten millions questions posted till 2015. Stack Overflow is ranked , by Alexa ranking, 70 out of more than 30 millions sites that are ranked. This number reflects the popularity of a website obtained by processing some information like the number of users who visited it during a particular time and the number of pages. To put things into perspective, Google has Alexa ranking of one. According to Stack Overflow 2018 survey to the users, JavaScript was ranked as the 7th most loved language, while Python was ranked third. The site state that JavaScript is still ranked as the most common programming language for the 6th year in a row, whereas Python was ranked on the 7th place. Node.js was ranked on top of frameworks, libraries, and tools used whereas Django was ranked on 6th place. Also, Node.js was ranked sixth in the category of "Most Loved Frameworks, Libraries, and Tools".[11]. All of this give an impression that Node.js adoption by developers has increased rapidly in the last years. Thus MeteorJS a framework written in Node.js was selected to build the application.

By using MeteorJS, one programming language, JavaScript, can be used for full stack development. Hundreds of thousands of packages can be installed using Node Package Manager (npm). Also, achieving real-time capabilities for the application was found easier using MeteorJS. MeteorJs is a free and open-source JavaScript web framework that is using Node.js. The main strength of this framework is that it allow for fast prototyping and can produce applications that run on different platforms like Android, IOS, and web. Meteor uses a technology called Distributed Data Protocol (DDP) that facilitate the real-time application by automatically sending the data changes to all subscribed and authorized users without the need to write synchronization code.

MeteorJS uses MongoDB database on server and kind of a lightweight version of MongoDB on the client called Minimongo. This approach facilitates replying to users interactions faster and reduce the time that is required for the server to reply. MongoDB is document-oriented NoSQL database which uses documents similar to JSON with schemas.

ReactJS, a library for UI building, is selected for front-end which uses the same language, JavaScript, that MeteorJS uses in the back-end. ReactJS is supported by Facebook company and is one of the most popular front-end frameworks in the market today. MeteorJS support ReactJS but it is not considered MeteorJS default frontend library (Blaze is the default library).

5.1.1 Selection of CSS framework

CSS framework is used to accomplish many outcomes including complying the design of web pages with standards, make them responsive and make the process of designing the UI easier by using Cascading Style Sheets language (CSS). The features that are offered by such framework include grids to manage responsive design, typography, set of icons, styling for components, user interface components like tabs, checkboxes, and buttons.

Many frameworks were examined to find a suitable one for this application. The focus was on the frameworks that use ReactJS including Material-UI, React Desktop, Semantic-UI-React, Ant-design, Blueprint, and Grommet. Criteria such us the popularity of the framework, the clarity of documentation, the size of components libraries and the support of responsive mobile design are among the factors that were considered in selecting a convenient framework. The first selection is made for Antd-mobile `https://mobile.ant.design/` which met all the preset required features except of having small community. Actually, Antd-mobile came with some unique features like exporting two versions of components one for the web usage and other natively run on Android and IOS systems using React Native. In other words, the code can be written once and it can work for many platforms natively, the browser, Android and IOS mobile phones. After experimenting with the Chinese Antd-mobile, I decided to stop using it due to the lack of comprehensive documentation and support in the English language.

Next, I selected Material UI which is considered one of the first CSS frameworks for React. The main factors for selecting this framework is the popularity of it and the fact that it supports Material Design guidelines, that are explained briefly in the previous chapter, by default. Responsive design that makes the page fit on small devices like mobile devices is supported by Material-UI. However, this framework cannot be used to generate native application as Antd-mobile.

5.1.2 Selection of Game Engine

To author a gamified interactive content for the user, a gaming engine that communicates with the user-centered database shown in the previous chapter is better to be used. If not, hard coding the games would require more effort to produce a rich game with multimedia, physics and proper rendering that would otherwise done using a game engine.

The term game engine was started in 1990 particularly with the famous game called Doom. In this game, the effort was made to separate the core software from art assets and rules of play. This made it possible for other developers to customize the game with new arts like characters and vehicles. Thus the term "game engine" emphasize on data-driven architecture that can be used as a foundation for creating many games without major modifications. This definition explains that a game which is a piece of software has particular set of rules that hard-code or render particular types of game objects that can not be easily reused then in other games. [34]. Game engines are written in different languages and the most relevant to this topic is those which are written in JavaScript language and which support HTML5. The game should integrate fully with the web application to read and write from/to the database of the web application that is built with MeteorJS framework and ReactJS.

JavaScript game engines including Phaser.js, Pixi.js, and Play Canvas were tested as part of the web application. The three gaming engines have high popularity and going through continuous updates. Recent releases were made for all of these engines in the current year 2018 [3]. Phaser is probably the most famous compared with other. In addition to game engines, WoofJS which is a library to simplify making games was also tested. The aim of experimenting with these libraries was mainly to bring the advantages of using game engines of games development and embed it inside a conventional web application by trying to build ReactJS game component that fit well with other application components like vote bar, sensor data, and navigation bar. The method of integrating a third party library with ReactJS was inspired by Stephen Grider [7]. Applying his method, all of the game engines worked well with MeteorJS and ReactJS except of WoofJS, where the author stated in his reply to the issue #519 on Github `https://github.com/stevekrouse/WoofJS/issues/519` that the library was not made to be used as React component.

The selection was made for Play Canvas as it supports building not only 2D games but also 3D games. The 3D capabilities of Play Canvas could be applied on other applications like virtual reality (VR). Play Canvas has an online cloud-based editor which allow a team of game developers and artists to work together. Also, Play Canvas support varieties of 3D files format such as fbx and obj. These files can be generated from many software like Sketchup, Rhino, Blender, and Fusion 360 [1]. Also, the fact that Snap Chat has purchased Play Canvas suggest that the engine may see an increase in its popularity and features in the near future [9]. This is due to the fact that Snap Chat worth billions of dollars and has a revenue that exceeded 800 million dollars in 2017 [5, 10]. The engine offers free cloud hosting for two projects and paid self-hosting. The engine can be used for self hosted games without additional payments. However, to download the games that are developed using the cloud editor, one should upgrade the plan from free to personal which cost 15$/month per seat. The main drawback of using Play Canvas is the lack of comprehensive tutorials and books. Yet, their website has many examples to discover and good documentation for the APIs.

RenJS `https://lunafromthemoon.itch.io/renjs` is also among the libraries that were tested and embedded in the web application. RenJS is a video game engine that can be used to easily make interactive visual novels that include characters with emotions, background images/wallpapers, background sounds, FX sounds and effects like raining and lightning that run on the web browser. The user plays as a character and watch the story evolve by interacting with the content in the form of textual questions which arise throughout the story. Figure 5.1 shows a silly basic example from our office with the character asking if the user like the proposed design of Aalto logo that appears on the screen (A with red heart on the right of it).

Figure 5.1: Textual question where user answer determine the next scene and story

Also, questions can be graphical images where user click on an image instead of textual content. The story can change according to users answers as shown in figure 5.2.

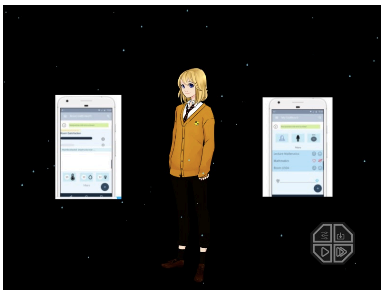


Figure 5.2: Graphical question where user answer determine the next scene and story

The scene has an effect of falling rain in the background combined with the rain sound. This brings liveliness factor to the gaming experience. The concept could be applied to varieties of questions and relate the answers with each user. The exploration stopped due to some difficulties making the design responsive and integrating the answers within the web application database. It is expected that these two issues are solvable, but the time that is required to solve them was hard to estimate. Thus, Renjs was not used in the final built application.

5.1.3 Achieving 3D Visualization

Visualizing the results to the 3D model is one of the goal features that is set in "methods" chapter. The results should be presented, for example using colors, in the place where it has occurred. Real-time interaction with the system from the users should be directly presented and added to the building information. To start with, an IFC file for Aalto Civil Engineering building was obtained to use it as an experiment file.

Three ways for accomplishing this goal were considered. The first was by using Bimserver `http://bimserver.org/` which is a software that build a cloud-based database from an IFC file format for data analysis and management [6]. Bimserver consists of APIs to provide visualization and other services to the web, plugins to render and edit the model and IFC based database. They claim that the old bimserverapi.js file was split into many files and that it is not loadable on Node.js `https://github.com/opensourceBIM/BIMserver/wiki/JavaScriptClient`. They ask the developer to let them know if, somehow, it get loaded. Since the web application is using MeteorJS which embed Node.js, no effort was made to try to communicate with the Bimserver using MeteorJS. In addition to this, Bimserver installation failed at first on my laptop due to incompatibility with Java version which then fixed after many experiments. Another problem that arose is related to the size of the RAM on my system. The conclusion is that the system which host the Bimserver should has at least 4Gb of free RAM not 4Gb of installed RAM. This was found in their documentation `https://github.com/opensourceBIM/BIMserver/wiki/Get-Started-Quick-Guide` which state that the heap size that is required to use Bimserver plugin should be at least 4Gb.

X3DOM is a JavaScript framework that can create 3D scenes using structured and textual representation (comparable to HTML) inside web pages without the need of any plugins. This way make the 3D representation part of the web page comparable to adding HTML text, image or a button. X3DOM consist of two words X3D and DOM, the first stand for Extensible 3D Graphics which is an ISO standard for declarative 3D graphics that has special subset of 3D contents that can be used inside the web page. The second describes the hierarchical representations that is part of HTML elements. X3D elements can be manipulated in the same way performed on other HTML elements inside the DOM using JavaScript. This includes changing colors and other attributes of X3DOM 3D element with JavaScript function setAttribute() using the same method that is used to change them for other Web page elements like, for example, the text inside a button.

One of the advantages that are obtained from using X3DOM is the usage of standard browser technologies like HTML5 and WebGL, thus no plugin is required. The similarity between HTML elements and X3DOM elements make it easier for a web developer to learn it without needing to learn new programming APIs.

Converting the IFC to X3D format and using a was performed. A free software that can perform such kind of conversion was not found, thus the conversion was not a straightforward process. By using ArchiCAD, it was possible to convert the file to Virtual Reality Modeling Language (VRML), a language that was found to define the 3D world and to connect them by the web. It includes graphical simulation for the 3D space and objects with some level of interaction. VRML allows multiple users to interact with one scene using a low bandwidth internet [23]. Using Blender software to convert VRML to X3D failed due to an unknown error. Using vrml to x3d online converter`http://doc.instantreality.org/tools/x3d_encoding_converter/` failed without showing any error. The process took endless time without any result. The web page `http://www.web3d.org/x3d/content/examples/X3dResources.html#Conversions` list many of the applications that can be used to convert different files formats to X3D format. Instant Reality provides some tools to play X3D scenes and other tool called AOPT to convert some file format to optimized X3D. Some explanation about AOPT is found on `https://doc.x3dom.org/tutorials/models/aopt/index.html`. The AOPT tool is found on MacOS in the path /Applications/Instant Player.app/Contents/MacOS/aopt and the conversion command should look like aopt –i myFile.foo -x myResult.x3d. Considering that ArchiCAD export IFC file to VRML, thus foo here should be wrl which is the extension of VRML files.

Despite achieving the goal of converting the IFC file, after some trial and error, to an optimized X3D the outcome was not satisfactory due to many reasons. The resulted X3D file was larger than the IFC file (around 4mb). The minimal size for X3D file was achieved using AOPT tool from around 27mb for the wrl file to around 9mb for the output X3D file. To reduce the original size of IFC file, some walls and columns were deleted. Embedding the resulted X3D file inside the web application resulted in poor performance. Figure 5.3 shows the converted file in x3d format opened in the web application.

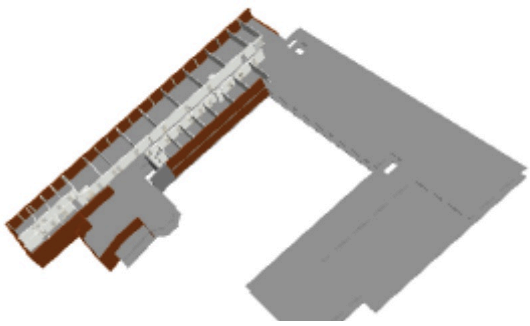


Figure 5.3: A view of Aalto Civil Engineering building in x3d file format

A potentially promising solution was to turn the X3D into binary or compressed X3D a solution that will make exchanging information with the web application and the 3D model not possible. The other problem was in defining the interactivity of X3DOM elements that did not work with ReactJS onClick event as shown in figure 5.4.

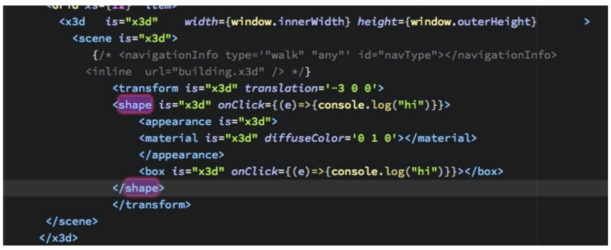


Figure 5.4: ReactJS onClick as defined in X3DOM React component

In summary, at least two problems arose with no accessible resources that explain how to fix them. No more effort was made to deal with these issues and another solution using Play Canvas was considered.

Due to the previous challenges, an idea emerged about using the Game Engine for two goals. The first is to build the interactive content for the user and the second is to visualize the data on the 3D model and build the interactive UI for those who are intended to analyze the collected data from the user like management, IAQ specialists and others. The IFC file of the building was converted into obj file format, that is supported by Play Canvas as explained earlier, using IFC Open Shell toolkit and geometry engine (`http://ifcopenshell.org/ifcconvert.html`). One of the tools, of IFC Open Shell toolkit, is called ifcConvert which can convert IFC to many other formats like IGES, Collada, WaveFront OBJ including .mtl materials files. The resulted obj file preserves the Globally Unique Identifier (GUID) for each element. This number, theoretically, can be used in queries to retrieve additional data from IFC files using Bimserver when needed.

5.1.4 The Sensors

A young Finnish company called Small Data Garden `http://smalldatagarden.fi/` provided the needed sensors. Figure 5.5 shows the device which has mini-USB power inlet and two hoses, one should be placed outdoor and the other indoor, to measure atmospheric and differential pressure.

Figure 5.5: Sensing device

The two round sensors on the top of the casing include a microphone to measure the noise and light sensor. The openings on the top are, probably, made to allow the air to flow from the room to the inner sensors that measure CO_2, NO_x, Ra, VOCs, RH% and temperature. Also, these holes may allow ventilation to prevent the heat from getting trapped inside as happened in the first delivered version of the device. In the first version, the reading of temperature was at least 5 to 7 °C more than the real temperature. The indoor temperature was around 25°C and the device was showing 32°C. According to the manufacturer, the problem in temperature readings was due to design issue. The modified version that is shown in figure 5.5 fixed the problem and the reading was compared with other Small Data Garden innovative portable temperature sensor. This small device, called IOTSU, figure 5.6. Contrary to the one showed in 5.5, it function on a battery that last up to 20 years and seems to produce less heat than the other device.

Figure 5.6: Portable sensing device

Both of the devices gave close results for indoor temperature. The small plug and play IoT devices are the central product of Small Data Garden in fulfilling their mission of "blasting the IoT market" and bringing the Internet of Things for everybody easily with flexible and cost-efficient devices. This small enclosure combine sensors, transmission, and processing units. The sensors that can be installed include distance, acceleration, motion, speed, NFC, RFID, CO_2, NO_x, Ra, VOCs, RH%, temperature, air pressure and differential pressure. [8].

IOTSU uses Sigfox low-frequency and long distance network to transmit sensors reading over the Internet. Sigfox is the first IoT network around the globe that receive sensors data without requiring them to establish and maintain network connections. The computing complexity occurs on the cloud to reduce energy consumption and costs (claimed to be 10x less than mobile subscription). [8].

The devices are capable to perform many sensing per minute and send the results every two minutes to the cloud (the time can be set). The device in figure 5.5 can sense the max and the average readings while the IOTSU transmit the average. We did not inquire about the possibility of IOTSU to show also the max readings. The data can be accessed using an application programming interface (API) or by web application provided by the company, figure 5.8.

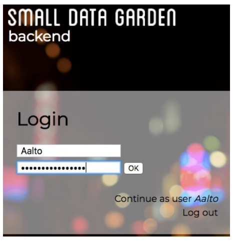


Figure 5.7: Small Data Garden login screen

After logging in the user see the devices that they have installed, the installed sensors in each device and a button to visualize different parameters figure 5.8.

Figure 5.8: Small Data Garden user interface

The interface is not yet mobile friendly, however, this may get some improvements in the future. The interface shows that there are two devices installed. IOTSU device shown in figure 5.6 measure only two parameters the temperature and humidity.

5.2 Building The Web Application

After planing the user experience and story, designing the user interface and selecting the tools like engines, libraries, and frameworks the actual process of building the application started. The resulted web application has most of the features that were planned. The following section walkthrough "lovol.life" web application.

The login screen figure 5.9 shows the designed logo which, in my opinion, comply with many guidelines presented in the previous chapter of simplicity and clarity. This logo correlate with the domain name or the web address "lovol.life" which make it easier for the user to remember it. "lovol" resembles a flying bird, the state that the user should achieve and "life" depict student life that mostly spent inside these rooms. Thus the metaphor of "lovol.life" is "student.life". The user starts his life inside an egg and grow by collecting points and interacting with the given content. The concept story of the badges is derived from a life of a bird.

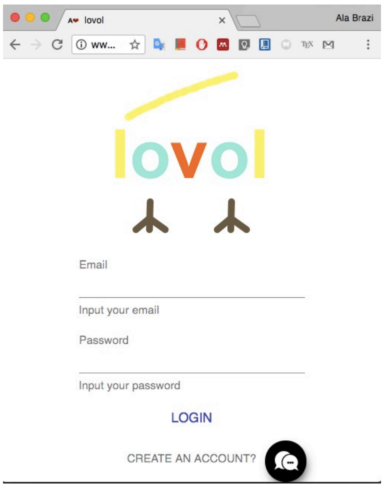


Figure 5.9: lovol.life login screen

After registration, the user is greeted with welcome screen that explains the system, what to do next and shows, humorously, the badge of the user as an egg with some signs of life figure 5.10.

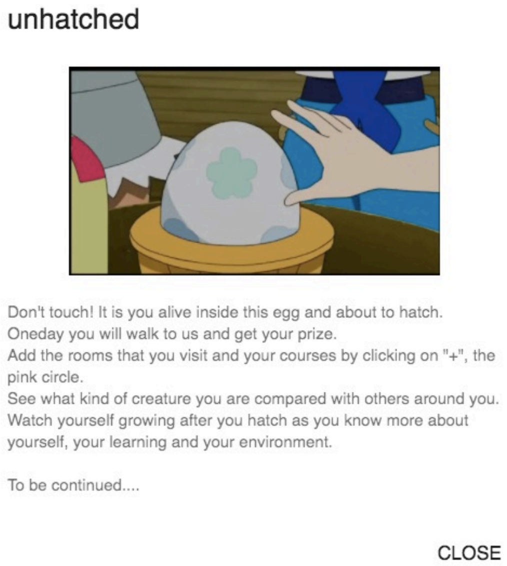


Figure 5.10: First screen after logging in
Source: https://giphy.com/ (the image)

Next, the user clicks on close and see the dashboard screen which is very close to the one presented in the previous chapter figure 5.11. The button on the right bottom corner is used to select rooms and lectures. According to Material Design it should be "accent" color to signal that an action of tapping is possible in this space. The "+" express that this button could be used to add/select something, in this case the courses that the user has and the rooms that the user visit.

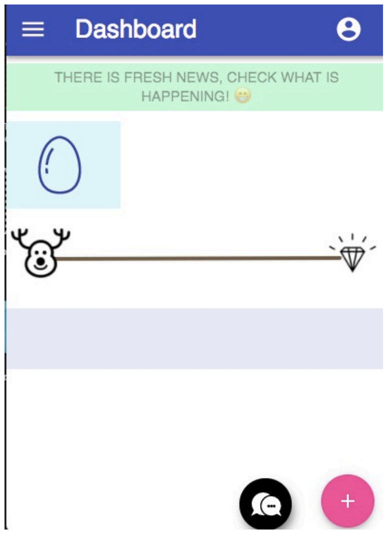


Figure 5.11: The dashboard of the web-application
Source: icons of egg, reindeer head and diamond from https://thenounproject.com

After selecting the courses, i.e BIM1, and the room, i.e U405, the user see that the dashboard has some content that requires interaction from the user. The user can rate the overall environment of room U405, the overall thermal comfort inside room U405, the overall satisfaction about the course (teaching methods, curricula ...etc) and if the user like/dislike the subject of the course. The intention is not to go into the detail of why the user like or dislike something but, as mentioned before, to see the tip of an ice berg fast enough to then analyze the bigger underlying problem. As the user participate the head of the reindeer move toward the diamond and the selected faces change colors to yellow to show user selections figure 5.12.

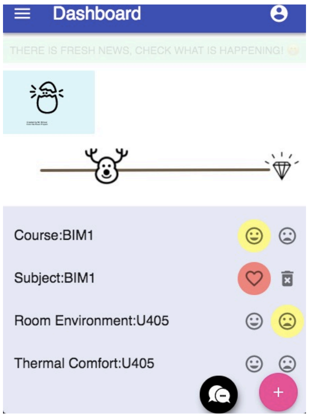


Figure 5.12: User rate rooms, thermal comfort and courses
Source: icons of hatched egg, reindeer head and diamond from https://thenounproject.com

The user is happy with course BIM1 and like the subject also. However, the user think that the room U405 environment is not overall good. The user did not rate the overall thermal comfort inside room U405. By participation, the user gets a new badge and became a hatched egg instead of unhatched egg. When the user collects enough points, the system congratulates the user for obtaining a new badge by popping up a dialog box as shown in figure 5.13.

Figure 5.13: User get a new badge when collecting more points
Source: https://giphy.com/ (the image)

The user can see more information about the average rating of room U405 environment by clicking on the gray bar figure 5.12 (either room environment or thermal comfort). Figure 5.14 shows room U405 information.

Figure 5.14: Room U405 info
Source: https://giphy.com/ (the image)

The information shown about the room U405 include occupants percentage of satisfaction and dissatisfaction in the room environment. In this case, 50% of occupants are satisfied with the indoor environment and 50% are not. If the current user clicks on the happy face instead, the user will see the blue bar filling to 100% in real-time. The user can not see the rating of thermal comfort for room U405 until participating in rating. The blue cards below show the user the current state of some parameters of the room that are obtained from the sensors. Clicking on one of these cards will open a dialog box as seen in figure 5.15.

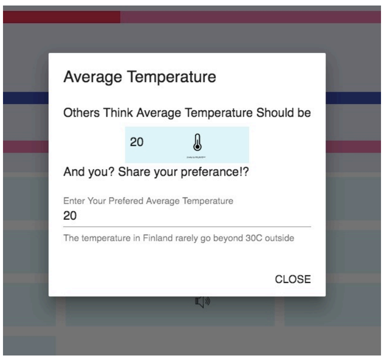


Figure 5.15: User select their preference temperature
Source: https://thenounproject.com/ (the icon)

The dialog shows the average wish for the temperature in room U405 and ask the user to enter the preferred temperature. The tip below help the user to put the current temperature into perspective. This information should then be visualized as part of BIM to help facility manager understand people wishes around the buildings and predict potential savings. It may make sense to reduce the temperature and save some heating energy if people prefer lower temperatures during winter. The green flashing box informs the users that there are some new interactive content that require attention, figure 5.12. Tapping on it take the user to happenings screen figure 5.16.

Figure 5.16: Happenings screen show two interactive contents
Source: Images from Google.com, React BMI component modified from https://github.com/

The first interactive content tries to understand the user cloth preference. This information is needed to estimate the PPD that was explained in previous sections. The second interactive content also collect some information about user weight, gender, height, and age by luring the user to know some information about their BMI. This information from the first and second interactive contents are sufficient to estimate the PPD and compare it with the actual votes (actual percentage of people satisfied/dissatisfied). The third content figure 5.17 is a game which added as a proof of concept. The game shows that integrating advanced gaming inside the web application is technically possible. Both, the games (the interactive content) and the web application can read and write to the same database. This means that a team of artists, designers, multimedia specialist and developers can work together to design an interactive content in the form of a game that aim to understand the user and collect information about them while at the same time entertain them. Developing a game that can do this was not accomplished in this thesis as it might be time consuming and require, in addition to programming skills, proper ideation of the game, graphics, and multimedia. These skills are multidisciplinary that, in my opinion, are harnessed better by setting a collaborative environment that consist of a multidisciplinary team. However, the game engine Play Canvas is linked with the database to visualize in real-time the state of thermal comfort and indoor environment on the 3D model for different rooms with smooth performance. This is a proof that the concept, of sharing a central database between React components that uses game engine and the web application, is working and can be applied to other games.

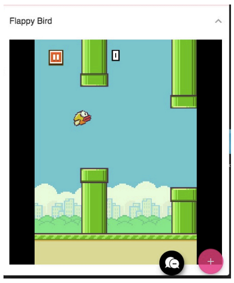


Figure 5.17: Flappybird game (ReactJS component) as part of the web application
Source: https://playcanvas.com/

The user receives new cards based on the answers in 5.16. By tapping on the card a dialog box appears which shows the category of the user and the percentage of similar users as show in figure 5.18

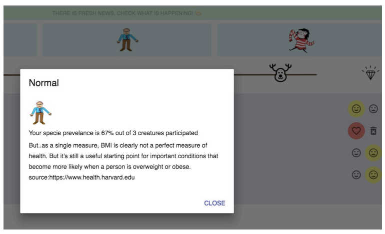


Figure 5.18: User receive cards and see what category belong to compared with other participants
Source: Images from Google.com

The user filled the information related to BMI content and thus can see to which category s/he belong. The category of user is normal (has good weight) the user represents 67% of the 3 participants (other users). The same concept applies for cloth preference.

The user can at anytime click on the black chat icon in the bottom corner of the screen and expect a direct answer to her/his concerns or question as shown in figure 5.19. When the user sends a message, the person who is responsible for replying get a notification or an email (if offline). This channel of communication provide fast feedback and act as an instant mean for reaching help very fast in relation to different matters.

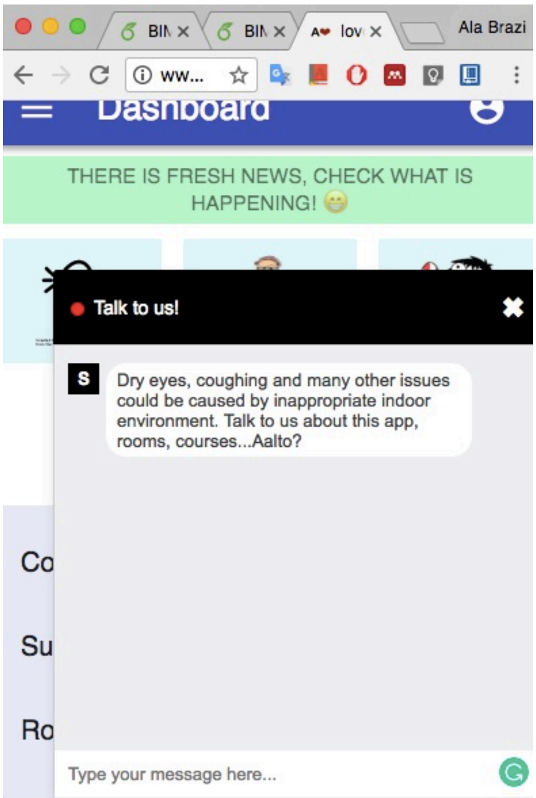


Figure 5.19: Chat service could be used to submit different concerns or questions

The results can be seen on real-time mapped to the 3D model as shown in figure 5.20.

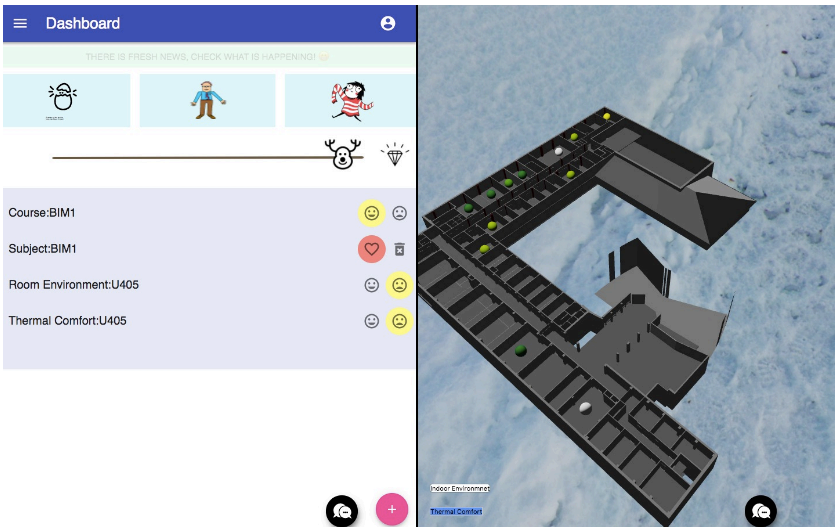


Figure 5.20: The user interface on the left and concept of management interface on the right

The state of thermal comfort is shown in Play Canvas 3D model (the button highlighted with blue). Rooms with white balls are not rated by users. Those with yellow has a thermal comfort level that should concern management and should signal the need for further survey or study. The dark green means that the sate is fine. The red balls show that the room requires instant intervention to examine the problem. The same could also apply for the indoor environment and other parameters if needed in the future.

5.3 Deployment and Hosting

The web application is hosted on MeteorJS European servers called Galaxy (`https://galaxy-guide.meteor.com/`). These are paid servers that have a tariff in relation to the size of the traffic used. The hosting service offers the developer the capability to expand the number of containers and increasing the number of CPUs and RAMs as their need increase. Galaxy belongs to MetoerJS and it is expected that hosting MeteorJS on their servers, yet not free, is a wiser decision than trying a third-party hosting. This assumption has got some validity as problems arose when hosting the application using Heruko free hosting service. The pink button color in the right bottom corner turned into white. Other colors like gray also turned into white and some colors that are supposed to be blue turned into red see figure 5.21. This issue is probably fixable but instead of trying to troubleshoot these problems, I just decided to stick with Galaxy from MeteorJS. The domain name lovol.life was acquired from `GoDaddy.com`.

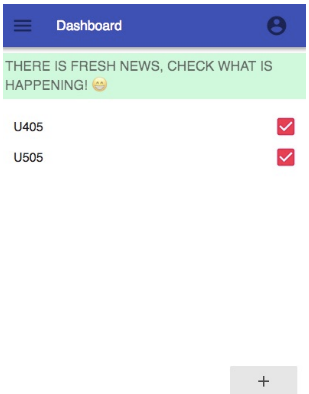


Figure 5.21: Distortion in UI when deployed on Heruko

5.4 Performing the Experiment

The built concept application was tested during BIM LAB breakfast event. Around 25 persons mostly students from Metropolia university attended the event. The users, mainly, used their mobiles to access the system. Most of the participants are studying a master and they come from outside of EU. Their major is mainly construction and real estate and they are studying at Metropolia University. Most of them are males in their twenties and there were only two girls. Indoor comfort or IEQ topics are irrelevant to their study program. Most of the users who followed the lecturer instructions interacted at least with some features of the system during the experiment session. Instructions about how to use the system and about the walk-through were presented. The users were asked to follow the presenter and use their devices to interact with the content. The intention was to get the first feedback about using the application to rate one room (BIM Lab) during BIM Breakfast event, to start with. This should give valuable and essential preliminary information for further developments to spot out problems and receive comments. This was the first usage of the concept design by many users at the same time and an experiment to see how random uninformed users perceive this system. The small group tests should precede longer tests with different kind of target users. When the groups are satisfied with the system and express some interest in using it further, a longer and more comprehensive tests can follow. The group testing and surveying is probably a good approach to start with. Design and development of a new innovation is an iterative process, thus performing a number of trials and error should evolve the system to meet users expectation.

The BIM lab is located inside the building on the ground floor and has no windows that face outside. The room is newly furnished with just the basic office furniture. The interior design is not finalized yet at the time of the experiment. The building seems to be one of the oldest in Otaniemi campus. The height of the roof vary inside the room. The device that has the sensors which presented earlier was used inside the BIM Lab to get the reading at the time of the experiment. Figure 5.22 show the room.

Figure 5.22: BIM Lab - Aalto

After the walk-through the participants are asked to discuss in groups their experiences, opinions and ideas. The users participated in giving feedbacks for further development. Some keywords to provoke the discussions was written on the white-board and the participant added relevant sticky notes under each topic. The main topics under feedbacks are:

- Usefulness: The usefulness of the web application and whether it will help to provide better learning and indoor environment.
- User Experience (UI/UX): The ease to interact with the system, the color used and the design of the UI.
- Stories/Content: Their impression about the story (from egg to bird), badges and the description of the badges.

- Rating System: If the rating system necessary and what kind of ratings they may want to have.
- Badges/points: Is using badging interesting? Do they like the badges idea.
- Other: Feedback about any other topic.

And the topics under ideas category are :

- Other applications: Are there other applications that the system can applied to like offices, hospitals and hotels.
- Additional features: Do the participants think that there are other features that can be implemented.
- Games/Stories: Games ideas that can be used to survey some information and stories that may sound appealing to them.
- Other: Any other ideas that does not fall under the given categories.

The lecturer explained to the participants the meaning of the above categories. Groups brainstormed feedbacks and ideas for around 20 minutes.

Chapter 6

Evaluation

The concept was built from idea, design to a working web application. Feedbacks are critical when evaluating new innovation. The built web application has met most of the guidelines and features that were determined in the methods section. The first users shared their first impression about the current features and what they expect from such application. The following sections evaluate the system from users perspective.

6.1 Users Evaluation

Users who participated in the first experiment during BIM Lab did not give further clear ideas for improvements. They mention "waste management" under application category and it was not clear what is meant by this. All the ideas that were suggested were not clear to me. When they are asked about giving feedback, however, many feedbacks were submitted. The usage of the application went smoothly without any problem. Regarding usefulness, two groups think that the application is useful. One group pointed out "GPS" under usefulness. They were not consulted of what they mean by "GPS". My expectation that they wish that if the application has the ability to locate their location in the building or the room. It was mentioned that the application could be useful in facility management. There is no skepticism arose under this category. The users liked the interface and the usage was smooth. They described it with words like good, user friendly and easy to use. The rating system for rooms, lectures and other ratings found needed by some groups.

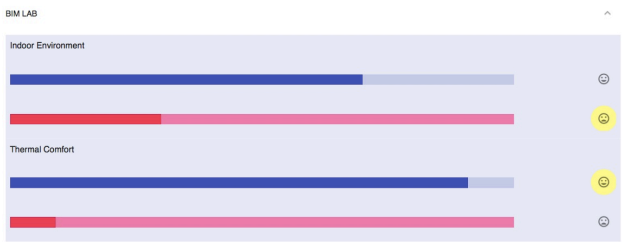
Groups showed concerns about the anonymity of the given data. One group expressed that a hierarchal access of data should be defined. In other words, adding a role of who access what should be clearly set. The users seemed to be afraid about misusing the collected data.

A group pointed out that developing a game to entertain and survey at the same time is not easy. Also, it may require developing so many games to collect data based on their opinion. Related issue concerned other groups as they listed money and costs as factors that require further thinking and consideration. Despite proven technically possible in this work, authoring and building games is demand resources not only to build the logical part but also to create multimedia, stories, characters, textures and other assets. Other group questioned the credibility of the given data form users. The accuracy of sensors is pointed out by one group. They advised to test the accuracy of the sensors.

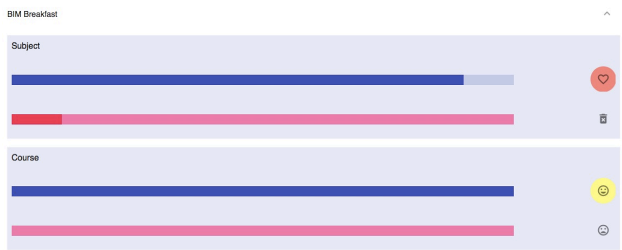
Some participants preferred adding a feature to have an avatar for themselves. At least two groups wanted a scale of rating rather than just two rating of happy not happy. One group wanted, in addition to rating, a comment service. The visual representation of the percentage of happy/not happy in blue and red bars were not sufficient for some participants. They would like to have exact number in addition to the bars.

A group in the first experiment think that the badges and points are needed. This group in addition to other group wish to have discounts and awards when they collect enough points. Some said that advertisement is a preferable feature in this system. Showing high scores for players is a feature that is liked by some participants. QR code also seen as a positive addition to the application.

The results of the 13 participants show that most of them were happy about the thermal comfort and less happy about the indoor environment as shown in figure 6.1. However, these particular results should not be taken seriously because some participant did not follow the instruction of entering accurate data. Few participants set the temperature that they would like to have in the room. One wanted the temperature to be 18 ° C. This is probably lower than the BIM Lab temperature which was unknown during the experiment due to technical problems in the sensors that are provided by "Small Data Garden". The company was unable to fix the technical problem in their provided sensors that happened during the experiment and caused wrong readings.



(a) BIM Lab room environment and thermal comfort ratings



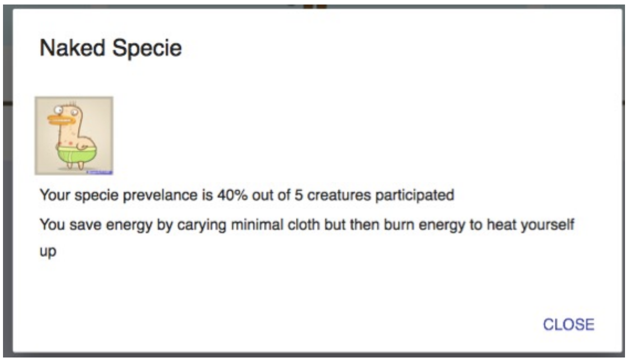
(b) BIM Breakfast event (subject/lecture) ratings

Figure 6.1: Users ratings

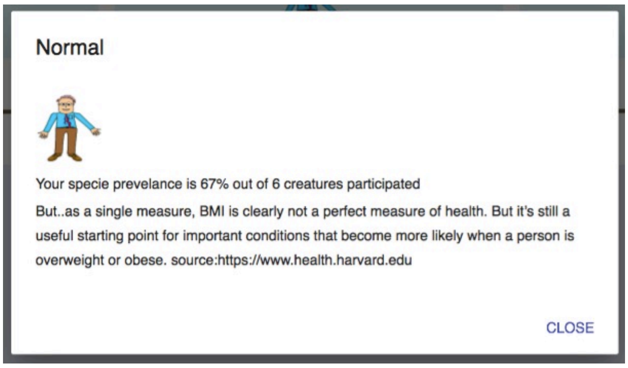
Concerns about irresponsible remote rating and how to prevent some students who never visited the place from rating it. Also, how to interpret these results and the criteria that determine the need for action. Should the management consider 10 negative rating enough to consider corrective action if the course has 90 students who never rated the course. The same apply for collaborative temperature control. Should the facility manager consider changing the temperature if there are 3 out of 100 wish that the temperature should be lower. The amount of ratings that are required to promote taking an actions for additional surveys should be determined.

Despite asking the participants of the first trail to follow the instructor during the walk-through and enter correct information, the results show that participants did not adhere to this. Some entered wrong age and weight. One user mentioned that his age is 300 years, weigh 200kg with height of 20cm. Other stated that his age is 12 years old. This probably happened because some users wanted to see all the available badges that they could get if they answered differently and see the picture of different badge category and read the description of each badge.

The data show, with this small sample of participants, that only 40% prefer to wear T-shirt or shirt indoor. 67% of participants has good BMI as shown in figure 6.2. This data seems to be correct as there was not many obese people. Yet it should not be considered accurate due to previously mentioned factors.



(a) Cloth preference



(b) BMI results

Figure 6.2: BMI and cloth results for one user

The lack of accurate data from the sensor, due to technical problems, and accurate input from users hindered the plan of calculating the PMV and PPD and comparing them with the actual rating.

Chapter 7

Discussion

7.1 Limitation of the Research

The accuracy of the used sensor was not tested against other accurate sensors. The first version of the device showed wrong temperature readings. The supplier did not submit information about the accuracy of the installed sensors. The sensors perform limited numbers of senses every minute and calculate the max and the average. The given data using the APIs attach this senses with the time when it was sent which happen every some minutes. This means that there might be a mismatch or some minutes delay between the send data and the real state of the environment. Also, this way of sensing does not properly sense the intermittent noises from, for example, slamming the doors that happen every other moment or from colleges speaking on their phones inside the office from time to time.

There are many limitations that hinders the comprehensive understanding of the user. The user health, psychological, financial and social state may all affect user comfort and opinion. These aspects are not examined at all. The number of students and location where the person sits, i.e close to window or heater, may influence the rating of thermal comfort. All of this ignored details may result in some kind of data noise when applied on large scale. The assumption, however, is that this noise may not be detrimental as the intention is to build general understanding not a detailed one. The chat service can always be used when the user feel that they would like to share some information or ask for help.

Adding more than two scales of rating is possible. However, in my opinion, as the number of rating increase it become harder for the user to make a decision. The goal as stated earlier, not to analyze deeply every aspect of the learning and the living environment but to spot any negative signs. Yet, an interactive scale or using some stars like in Amazon rating of products could be used instead of good/not good rating.

To get useful data, users should input their real opinion and unbiased data to the system. Starting with random users is not suggested. Instead, the system should be examined, in my opinion, with a small well informed group of participant who are selected and agreed to be dedicated to give accurate inputs and feedback at this experimental stage. Also, using sticky notes is not recommended to communicate ideas that need further explanations from the users without inquiring about the keywords that they have written. The survey, in paper or in digital format, is better to be given to the users directly after using the system instead of asking them to fill it after they leave. Adding a feature to the application that summaries the inputs and list the participants inputs in a table would facilitate the supervision of the entered data to spot the irrelevant input easily.

UCD suggest that the approach for usability in this work was not sufficiently apply all the recommendations to design for usability like having a team of multidisciplinary professional and to involve well informed responsible users in design at an early stage. This was not done as it was required to have a functioning concept beforehand. Meeting the deadline that was set for this work limited the time reserved for testing and preparation phase. Research and development projects required approaching wide spectrum of multidisciplinary topics that usually done by a group of professionals.

7.2 Future Improvement

Requesting the user to select their location and courses contradict with the guideline that was set when designing the interface. The system should have access to Aalto database and get information about user courses. Both databases should exchange data with each other. The location of the user can be determined without the need of the user to input it manually by giving each user, for example, a bluetooth device as shown in figure 7.1 for location monotoning that can be turned off if the user wants to. The student can receive such device when they are admitted to study and return it when they graduate.

Figure 7.1: A device to track location inside the building

To prevent remote rating for courses or rooms from students who did not attend the lecture, the system can allow rating only when the user is having the course (by reading from Aalto students database) and only when s/he (the bluetooth beacon) is physically close to the lecture during the time of the course. However, in my opinion, the first implementation should rely mainly on trust and sense of responsibility because all of the added feature will require extra setting and costs which make the application more complex, require charging the devices that detect location, turning the beacon on/off and to deal with additional problems that might be caused due to poor bluethooth signal or drop in signal. After all, the rating could be meaningless even with all of the technology applied when people choose to be biased in their judgment. Also, the rating could be supervised by the teacher after each lecture. For this, it is possible to generate a specific code so that only students inside the lectures can see it and then rate the relevant lecture. But again this add additional steps that make the user experience worse. Entering passwords and scanning bar codes is,probably, not interesting for the user. QR might be helpful if it can reduce the steps that are needed to perform particular task like selecting a room. The best solution for this could be studied further in the future.

Gamefication of surveys require enough resources and a lot of ideation and brainstorming. It require multidisciplinary teamwork to create an interesting content. Adventure and novel games seems to be the best type of games that are suitable for collecting information. The user choices in the virtual life give data about whom s/he is in real life. The user play a game and required to take decisions to deal with incidents that arise. This idea is similar to the one presented earlier using Renjs. During the virtual life the user learn about Finland and Aalto and the university know more about the students choices which govern the story of his/her virtual life. High scores reflect how good the user choices were and the advancement in playing and in creating knowledge by playing. The creation of interactive contents and games may help different departments understanding, entertaining and educating users. This might be costly to do and require a lot of resources, as pointed out by some of the first users of this system. Further explorations should be considered to find if the gains do worth the spent effort.

Adding numbers to the vote bars as suggested by users is easily doable. In my opinion, this will make the interface less appealing because visual presentation of information is preferable over textual and numerical. Seeing the red and blue bars give approximate understanding of the state of the room. All in all, this is minor issue because the database store the accurate percentages of rating and visualizing them in numbers or not, is just a matter of a design choice.

Avatar badges and points are considered positive addition to the application by some users. Also, showing others game score is preferred by some. Users like to have promotions, coupons, discounts or prizes and all of these should be considered in future developments.

Experimenting with transdermal optical imaging (TOI) which can use conventional cameras to capture the changes in the blood flow across different level of the skin to predict the emotional state of the person could be performed in the future. It is claimed that this technology can predict physiological parameters like heart rate, blood pressure, respiration rate and cardio stress in addition to psychological state like mental stress and emotions including joy, sadness, boredom, and fear. This technology requires installing cameras and proper lighting. This would serve two goals, first to get images of the indoor environment and second to understand occupants emotions without requiring their input. The application of this technology in lie detection showed promising results. It outperformed all kind of specialist and were able to detect lies in more than 80% of participants. [4, 59]. It could be possible to automatically attach the emotions with the user and then the user can confirm it or change it if it does not reflect the real state. This system if proven functional, is essential in understanding the users without even needing any input from them.

Integrating wearable devices into the system where the user could choose to allow the system to access information about them from their personnel devices could also be a topic of further study. Some devices can give information about the user physical fitness and stress level. The accuracy of stress detection of such devices is increasing and they are already used to detect stress in the working environment. [35]. But the accuracy also varies according to the application. These devices, for example, are more accurate in detecting physical activities than the time user spends sleeping [26].

The data collection requirements of varied departments in the management should be set to determine what is the information that they may need to know and visualize in order to support their decision making. The interface for each department can vary according to their needs. The facility management may be more interested to know about the user subjective thermal comfort at different places of the building throughout the year and set the temperature to suit wider circle of people. A low rating of a particular indoor environment may correlate to the interest of many professionals like the facility management, IAQ professionals and interior designers. The reason for low indoor environment rating could be improper lighting or acoustics. It could also be related to IAQ like a high level of CO_2. The design of the space which has industrial ducts and dull colors without windows could also lead the user to rate the indoor environment low.

Having more sensors inside the rooms that are attached to the system would help to make a better judgment about the cause of an issue. In the future, 3D photos could be added to the system to be accessed by management or could be added to the 3D model in the form of textures and VR.

The current system register only the last state the user input. It may be useful to record how the rating changes over the time as seasons and other parameters change. This gives understanding of the changes of rating throughout different seasons and different indoor environment parameters.

The application of this system could be extended to other sectors including offices, hotels and hospitals. The main parameters that are specific to each application should be determined by experts from different fields. Tagging and commenting,as suggested by users feedbacks, could be used to show specific unique features (strength/weakness) of each space.

Crowd settings of temperatures and other climate parameters, by users, should be researched further to determine the feasibility of such system. The system may take action automatically using some AI algorithms to maximize comfort that take in consideration many criteria like the number of users in the space at any given time, the type of the users and the building, the age of the users in the space, the range of the allowed temperatures deviations, the time of inputs and the number of users that requested the change recently. A weight can be given to each input according the type of the users to prioritize the inputs of particular users. For example, if there is an office with ten fit young occupants out of ten possible occupants who prefer the average temperature, according to their votes, to be 20C in winter then a temperature of 25C during the whole winter is a waste of energy. The system should be, at least, able to deal with such kind of cases that has high certainty rate automatically.

Few teachers in Aalto collect sticky notes feedbacks after each lecture. This system could be useful to them by reserving two minutes after each lecture to rate the lecture. After all, probably spending minutes rating a lecture when needed is better than spending so many hours each month attending poor lectures. After each lecture, students can either keep their previous rating or modify it. The teacher can give some kind of incentives to those who participate in rating the course, room environment and thermal comfort. Users do not, necessarily, need to rate every single lecture but rather change their rating if their opinion changed. It maybe helpful in the future to examine the relationship, if any, between the level of cognitive thinking required by a subject and the thermal requirements of the room. Iterative design and test should shape the final features of this system.

Chapter 8

Conclusions

Humans comfort is a complex topic and is rarely visualized. Providing a proper thermal indoor environment and better IAQ in living places improves productivity and reduce sickness. Improving IEQ is also expected to increase occupants comfort and productivity. The current way of gaining information about occupants rely mainly on questioning and surveying and offering gifts to random users. Using this method may not motivate many users to participate specially if the questions are lengthy and need cognitive thinking. Few participants may not be sufficient to comprehend the real state of the survey topic. Also, such kind of surveys are usually old as they are conducted every some months.

Human thermal comfort is explained briefly including adaptive comfort and the indices that are used to estimate it. IEQ effects on comfort including IAQ were presented. Achieving optimum comfort in the built environment is a complex process.

Questionnaires are used to assess the subjective comfort judgment in comparison with the data transmitted from the sensors or those estimated using PPD. Short questions that do not require cognitive thinking are used to maximize participation and get faster responses. There are many advantages that could be achieved by embedding gamification inside the system. UCD is the key for having a product that is loved by the user.

A concept platform which combines two UI, one for students and the other for management, i.e IAQ professionals and facility managers, was designed and developed. Gamification is used in order to engage more users to give inputs by using interactive content and playing surveying games. The spatially mapped and visualized real-time parameters about users living and learning environment might be considered valuable to the management to promote fast corrective measures and spot potential improvements.

The developed system has simple and mobile friendly UI with central database that store inputs from users and sensors. It applies many aspects of gamification like badges, points, interactions, comparison with other users to render positive users experience and prompt more participation. The system can make the user aware of the parameters of indoor environment in each room. It can act as the main ranking and evaluation systems for building IEQ. It integrates chat service that can be used to get help in cases related to IAQ symptoms and other needs related to indoor environment. Also, it visualizes the data in real-time as part of BIM. A proof of concept was shown by visualizing the building information on the 3D model using a gaming engine which read from the web application database. More advanced surveying games, i.e using VR and novels, can be developed and added to the system.

An experiment was made to evaluate the usability of this software from the user perspective in order to drive future developments. The results show that the application was easy to use and user friendly. Some users think that rating different aspects of learning and indoor environment is valuable for them. Badges, points and games are found useful and entertaining. Moreover, some think that having prizes, coupons, and discounts will motivate them to participate further.Showing avatar and the points of users may make the platform more appealing to some users. Many preferred scaled rating of many scales over two scale rating of happy/sad. The anonymity of rating and the security of data access were concerning for some users. Some users wished to have QR scanning and automatic location determining system. The expenses of developing such kind of platform is questioned by some of the participants. The development of an algorithm to determine when to intervene to take corrective action, yet not studied here, may require further study in the future.

Future developments should tailor this system to meet users wishes and reduce the need of user inputs. The system should know the location of the user automatically and determine the courses that the user has based on the user location. This could be achieved by accessing the university database to get information about the courses that each student has. It also requires giving each student a tracking device that can know the location of the student inside the university buildings. Reducing the need for user input could be extended further by investigating the potential of using TOI which could predict the physiological and the psychological parameters about the user by using conventional cameras. Wearable devices can be used, if permitted by user, as a source of additional information like heart beat, level of stress and average number of sleeping hours. The abundance of information with proper data analysis algorithms may increase the indoor environment quality, optimize the use of resources and increase the quality of life.

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Appendix A

First appendix

A.1 Users Feedbacks and Ideas

Users feedbacks that were submitted during BIM Breakfast is shown in the figure A.1. Some of the titles were not clear as they are located on the upper edge of the paper. Thus "User experience" and "story/content" are added to explain the category that, should, belong to the sticky notes. However, users did not strictly follow the rules and sometimes they placed the sticky notes under wrong category. The content that were not understood are ignored from the evaluation of discussion section. As I mentioned before, the users were not asked to explain everything they have written on sticky notes.

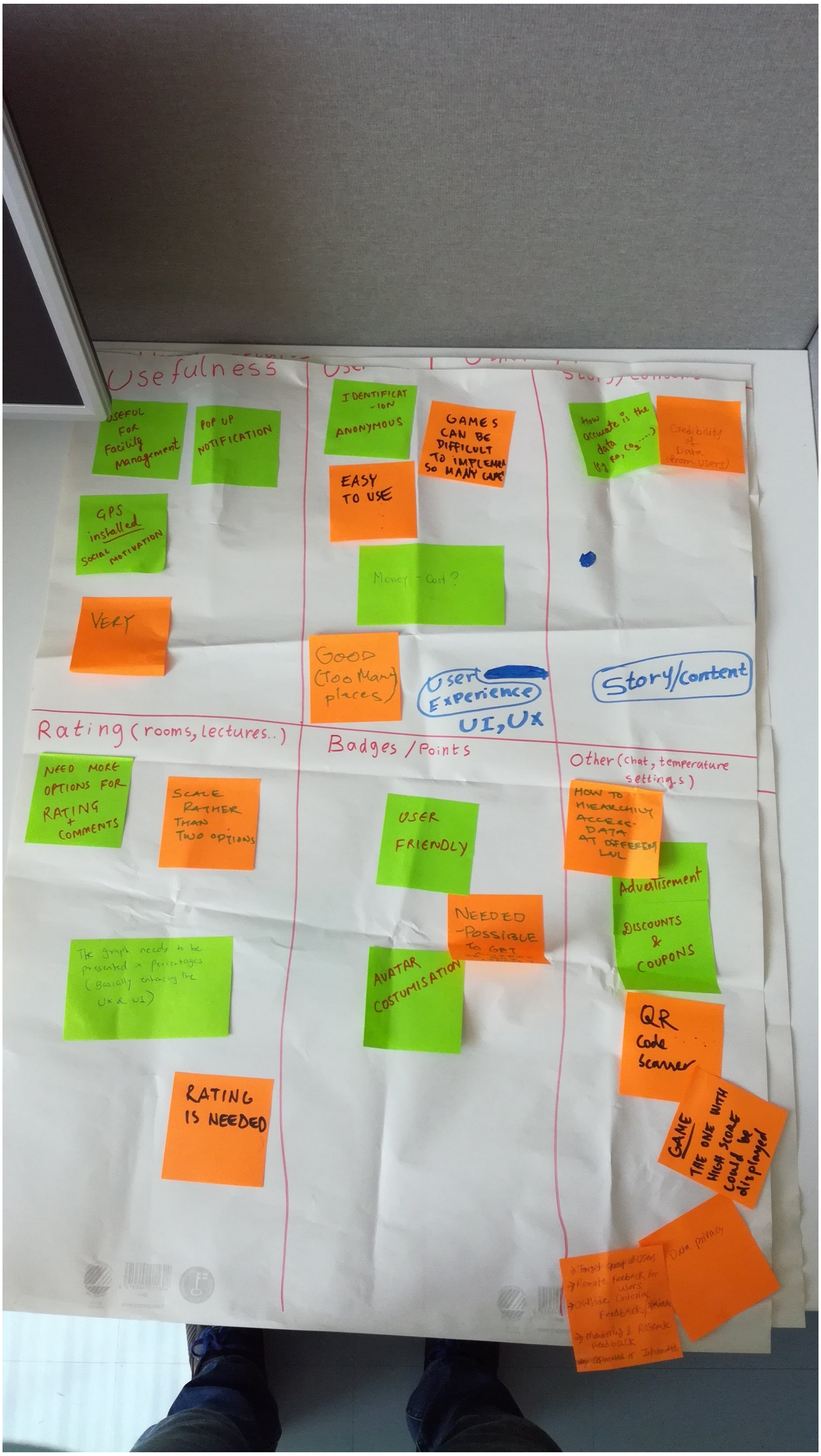

Figure A.1: The feedbacks submitted by the Users

The ideas that were submitted, A.2, were all ignored as they were not clear.

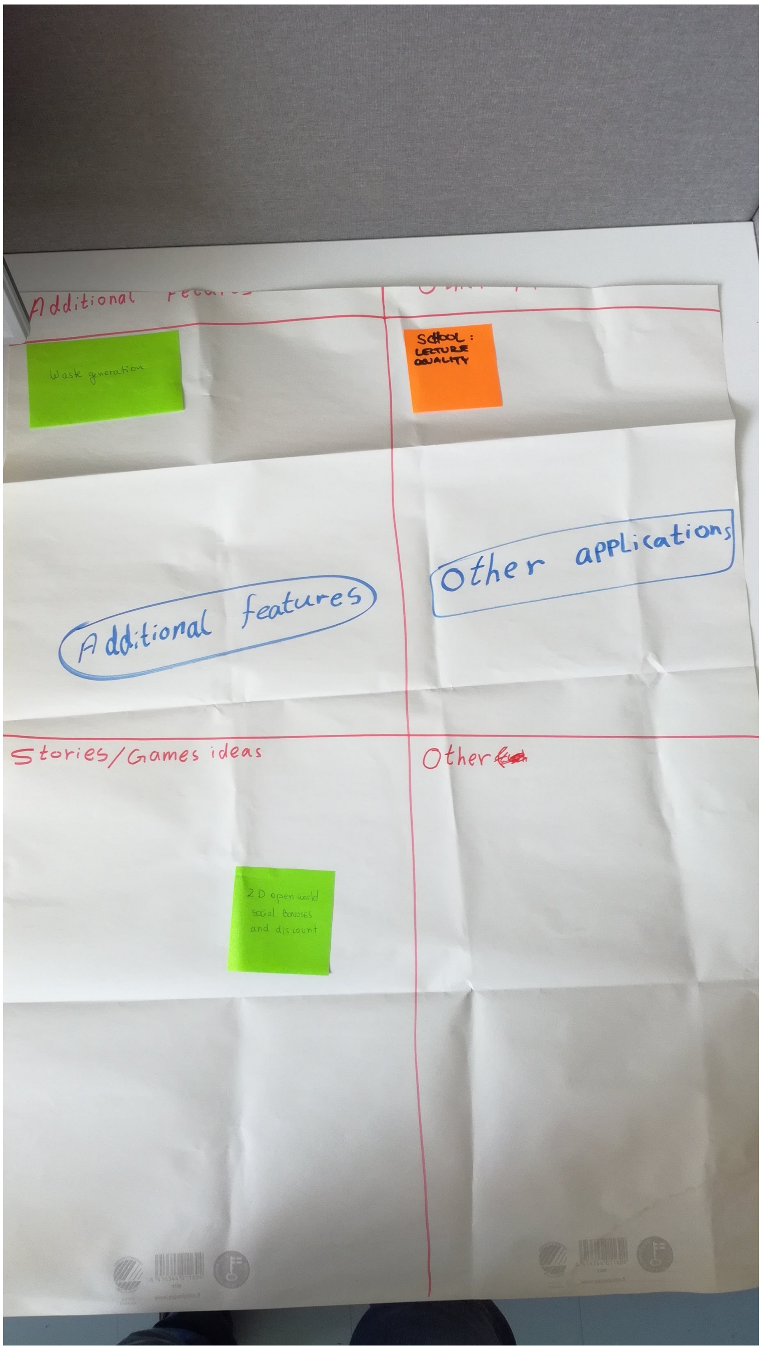

Figure A.2: The ideas submitted by the users