Refurbishment of Ventilation in Respect of Indoor Environment Quality and Energy Efficiency

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1 BACKGROUD FOR SUSTAINABLE INDOOR ENVIRONMENT

In a sustainable building environmental, human health and wellbeing as well as lifetime cost issues need to be considered. Many environmental ratings like LEED in the USA or BREEAM in UK take into account various aspects in building itself, management of building, and also the health and wellbeing of users. As buildings are built for people, the human issues should always have some priority when selecting from various environmental options during design and use of buildings. Lifetime costs are important to developers and owners of buildings and therefore both potential cost savings and increased value of building are of great interest.

1.1 Indoor Environment Quality is Essential for Human Health

Everyone has a right to healthy indoor air. Indoor air quality is an important determinant of population health and wellbeing. Exposure to the hazardous airborne agents present in many indoor spaces causes adverse effects such as respiratory disease, allergy and irritation of the respiratory tract. People in modern societies spend most of their time indoors; at home or work, in school and in transit. In average, we spend 90% of our time indoors. Improving the quality of indoor environment enhances both our wellbeing and our performance. In healthy indoor spaces thermal, sound and lighting environments are comfortable, there are no known contaminants at harmful concentrations in indoor air and with which a substantial majority of people do not express dissatisfaction. The following factors affect our perception of the indoor environment:

- *The amount of outdoor air.* Every one of us needs 12 cubic meters of clean air to breath per day.
- *Thermal balance with our surroundings.* Thermal balance is a result of various environmental conditions, all of which can be affected by indoor climate systems.
- *Acceptable indoor air quality.* In general terms, the indoor air quality is acceptable when it doesn’t contain contaminants in harmful concentrations and the majority of people feel satisfied.
- *Lights and sounds.* Light is the most important factor influencing our daily rhythm. Lights too bright as well as disturbing discussions and other sounds cause irritation and increase the negative stress hormone level.
- *Personal factors and preferences.* The comfort sensation depends partly on the individual: the metabolism, the activity level of body and the clothing resistance.

1.2 Good Indoor Environment Quality

Indoor Environment Quality (IEQ) covers fields of specialization include thermal comfort, indoor air quality (IAQ), acoustics, lighting, control systems and architecture. In total, the indoor experience is known as the indoor environmental quality (IEQ).

Human thermal comfort is defined by ASHRAE as the state of mind that expresses satisfaction with the surrounding environment. Thermal comfort is affected by heat conduction, convection, radiation and evaporative heat loss. Thermal comfort is maintained when the heat generated by human metabolism is allowed to dissipate thus maintaining thermal equilibrium with the surroundings. Any heat gain or loss beyond this generates a sensation of discomfort. In comfortable thermal environment room air temperature is individually adjusted to right level (typically 20…24^{O}C), is not varying frequently and air temperature difference between floor and ceiling is less than 3^{O}C. Window surface is not too gold (above 14^{O}C) or warm (under 30^{O}C). Direct solar radiation is prevented with effective shading.

Draught is an unwanted local cooling of the body caused by air movement and temperature. It is the most common complaint in many ventilated spaces. Draught feeling can be avoided by designing thermal environment correctly and allowing individual control as well as avoiding too high air velocities especially in intermediate seasons and wintertime. Typical room air velocity in the occupied space is between 0,1 and 0,25 m/s. Often drought is a result of technical problem in HVAC system, e.g. unbalanced ductwork or badly directed air diffusion. Sometimes down draught and radiation of gold window surface generates it.

Good acoustic environment is dependent on the use of space. In a cellular office, wall structures and doors are used to isolate the airborne sound from surrounding spaces. In addition, the airborne sound inside the room shall be sufficiently absorbed. In open plan office spaces the background noise is used to cover sounds from surroundings and therefore improving acoustic privacy. The main target in the acoustical design of meeting rooms is that the participants are able to hear and to become heard. This can be reached by low background noise and low reverberation time.

In good lighting environment working surfaces are sufficiently lighted (a. 500 lux) and there is no harmful glares. Good contrast conditions can be created using indirect lighting (a.70%) and good modelling conditions by using direct lighting (a.30%). Aesthetic environment have soft transformation between dark and light areas.

Indoor Air Quality (IAQ) deals with the content of interior air that could affect health of building occupants. The IAQ is compromised by microbial contaminants (mould, bacteria), chemicals (VOCs, formaldehyde, radon), particles (mineral wool fibres, fine particles, dust) or allergens, which can induce health effects. Indoor air quality can be improved either by eliminating the internal pollution sources or diluting them by ventilation. Whenever air intakes are not controlled and untreated outdoor air comes into building, also the quality of outdoor air may generate a health risk. Minimum fresh airflow rates are defined based on national building code.

1.3 Effects of Inappropriate Indoor Environment

Several hundreds of thousands of people die too early due to environment in Europe each year. Increased hospital admissions, extra medication and millions of lost working days are not only a financial issue but above all they influence the quality of our everyday life.

There are many effects of inappropriate indoor environment quality, like increased need to keep breaks during work, decreased concentration or fatigue. In extreme cases problems can lead to absence from work due to permanent or temporary health effects like headache, eye, skin, throat or nose irritation, thermal stress, allergy or asthma.

If indoor environment is not systematically maintained and developed, people are exposed to inappropriate indoor environment. This creates wellbeing debt, which in long term can lead to temporary or permanent health effects and thereby absence from work. Often these symptoms are not immediately eased even the indoor environment is improved and refurbishment dept is diminishing. Although the quality of indoor environment is in high level after construction project is finished, often the IEQ starts to decrease gradually due to low maintenance of indoor environment and technical systems. There are also many changes during the lifetime both in size and usage of spaces, but no alteration in technical systems are made. These increase the refurbishment debt of building, but also the wellbeing debt of users in the building (Fig. 1).

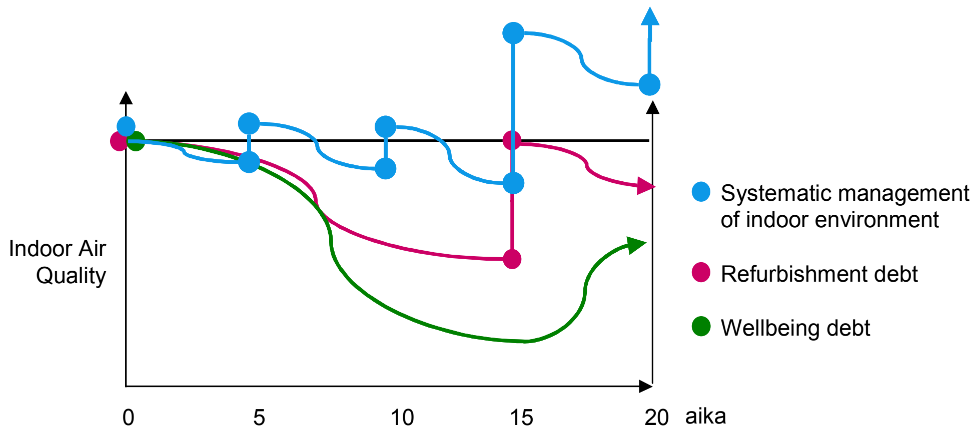

Figure 1. By managing and developing indoor environment systematically, indoor environment quality can be kept at higher level continuously, and therefore both the refurbishment and the wellbeing debt can be reduced.

Tobacco smoking is the biggest indoor air quality problem. This is why smoking is already prohibited in indoor spaces in many countries. Solvents, paints and other building materials as well as aerosol sprays and dry cleaning may release volatile organic compounds (VOC) into air. Moisture damages can create serious indoor air quality problems. Growth of mould starts in wet structures. Regular maintenance of building improves the indoor environment, ensures well operating technical systems and prevents refurbishment debt of building but above all it prevents the wellbeing debt of users.

Indoor environment can create dissatisfaction and health problems for users due to various reasons. Often the reason is the performance of technical systems. In many cases technical problems are local and that is why it is difficult to find and locate them. Occupants complain about too hot or too cold temperatures during summer, too hot or too cold temperatures during winter, and draughts from ventilation system, stuffy or stale indoor air or lack of sound privacy in open plan offices. (Fig. 2)

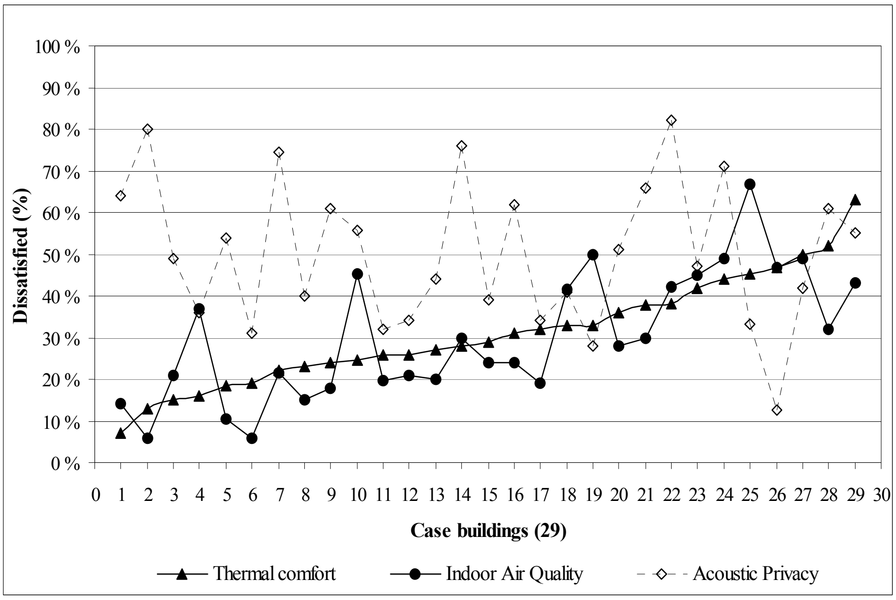

Figure 2. The percentage of the dissatisfied on thermal comfort, air quality and acoustic privacy in 29 buildings. Case buildings are binned in the ascending order of dissatisfied on thermal comfort.

1.4 Financial Benefit of Good Indoor Environment

Good indoor environment improves productivity quicker than changes in working habits or skills, especially if indoor environment has not been in focus before. In a typical company operating in office environment 90 % of total company costs consist of employees' salaries. The rest of the costs include workplace related investment and running costs. International research has proven a development of 2-10 % in workers' productivity, when indoor environment has been improved. A minor 1 % (5 min/day) increase in office work can off-set the annual cost of ventilating the building. The full costs of installation and running the building can be off-set by productivity gains of just under 10%. A reduction of indoor air temperatures above 22 ^{O}C by 1 ^{O}C can roughly increase the performance of office work by 1%. Doubling the outdoor air supply rate can reduce sick leave prevalence by 10 %, and increase office work by 1,5%.

1.5 Energy Efficiency of Ventilation Systems

There are several ways to save energy in office building. Well-insulated, tight structures are important in low energy building. Also the shape and the orientation of building are important in terms of energy use and how massive the structures are i.e. they ability to store energy. Increased levels of insulation and better air tightness have reduced the heating and cooling requirements of buildings. However this is not enough to achieve best energy ratings. It is also important how mechanical systems are designed and used. Efficient solar shading during the cooling season and utilisation of solar heat during the heating season are important. The use of artificial lights should be limited to minimum and instead the daylight shall be utilised as much as possible. All electrical equipments shall be switch off when they are not in use and when possible the low energy equipments should be used.

Today ventilation represents about 20 % of total energy need of building and in passive buildings it can even be almost 50 % of total energy need. A good ventilation system must be controllable in response to the requirements of the buildings occupants. This is often difficult to achieve because the total ventilation rate of a building is a mix of mechanical or natural ventilation and unintentional air leakage.

In a good mechanical ventilation system following design criteria are taken into account:

- the air tightness of the building envelope;
- the method of air supply and exhaust;
- the control of ventilation system
- room air distribution.

Ventilation is needed to provide fresh air for occupants, to dilute and exhaust pollutants from indoor air and to provide some cooling. Ventilation is also needed for the protection of the building and elements of its construction against moisture. Low ventilation rates reduce comfort and can be a health risk for users. Too high ventilation rates increase risk of draught. It will also incur an energy penalty both in heating energy and as an increased need of dehumidifying the supply air.

Traditionally, ventilation was uncontrolled due to their leaky construction, chimneys and unsuitable components, which meant that buildings were difficult to heat, to maintain comfort and keep dry. Since the 1970's buildings have become more energy efficient.

2 IDENTIFICATION OF PROBLEMS AND UNDERSTANDING OF VENTILATION SYSTEM OPERATION BEFORE REFURBISHMENT

Regardless of importance, indoor environment management process is currently very fragmented. There has been no continuity to the process through the building lifecycle. Especially, the very early phase (identification and understanding of problems) as well as commissioning and operation phases have been recognized the biggest potential to enhance indoor environment quality (IEQ) in an energy efficient manner.

The objective of this value adding process is to make it possible to first understand problems related to operation of existing ventilation system, providing right solution during design phase and securing operation. The target contains human comfort, environmental, and economical considerations.

Before starting the refurbishment of ventilation system it is important to understand the operation of existing system. Sometimes the problems are fundamental and therefore require a full refurbishment but sometimes there is no need to re-build the entire ventilation system.

A systematic method for assessing and improving indoor environment quality (IEQ) in existing and occupied office buildings is important. The method is recommended to start with occupant satisfaction survey that is directed to everyone working in a building. Questions focus on the human experience of indoor environment. By using occupant satisfaction survey all comments, also the silent, can be collected and taken into account when making decisions of improvements. A technical analysis requiring multidisciplinary knowledge is conducted in building areas where respondents are dissatisfied. Systems creating and maintaining indoor environments consist of many components that are usually provided by different companies. Cross-scientific team of people representing various aspects of technical services conducts the technical analysis in the building. Improvement actions are determined based on the results of the survey and technical analysis.

When analysing occupant feedback, there is two major complaints regarding ventilation: ventilation generates draught or room air is stuffy.

Draught is the most common complain in occupied spaces. The reason behind it varies. Poor air diffusion due to wrong size or type of terminal unit compared to the airflow rate is one of reasons. Especially important is the location of workstations in relation to air jets in the space. Sometimes the air jet is wrongly directed towards the workstation. Furniture or light fitting can be too close the terminal unit and disturbs the good air diffusion. It is possible that the air jet turns down too early due to too cold supply air temperature or too low pressure level inside the terminal unit. Also hot or cold window surface can change air diffusion in the space. (Fig. 3)

Figure 3. Typical reasons for draught generated by ventilation system.

Process to solve draught problems often starts, when users contact facility management people and complains about draught. Facility management typically solves the problem by increasing the supply air temperature. This easily leads to another problem elsewhere in the building. Room air becomes too warm and people feel it stuffy. Increasing fresh airflow rates then solves that problem. This creates another draught problem and increases the energy use. When the real reasons for draught are analysed instead and air jets are re-adjusted in those areas where that is problem, lots of energy can be saved and negative treadmill can be avoided. (Fig. 4)

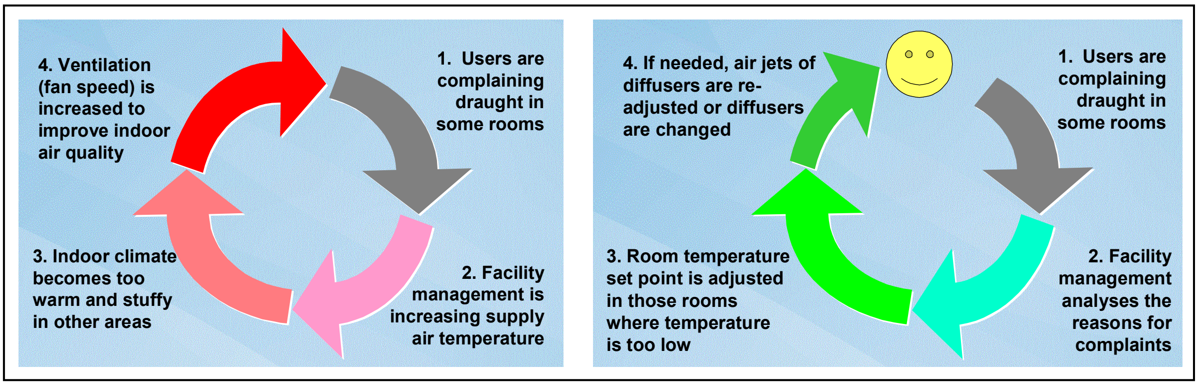

Figure 4. Negative and positive treadmill to solve draught complains in office environment.

Reason for draught complains is not always the ventilation system. Sometimes people feel too low room air temperature as draught. Especially when combining it with high air movement. This happens not only during heating season, but it can be a problem also in cooling season. Cold window surface generates high air velocities (Fig. 5) and at the same time the cold surface near person increases radiant heat transfer from human body. By changing better windows into a building both energy efficiency and human comfort can be improved.

Figure 5. Cold window surfaces can be a reason for draught complains.

Stuffy room air complains with simultaneous draught complains elsewhere in the building can be a consequence of unbalanced airflow rates in the building. (Fig. 6) In most of these cases it is enough to re-commission the ventilation system and big refurbishment is not needed.

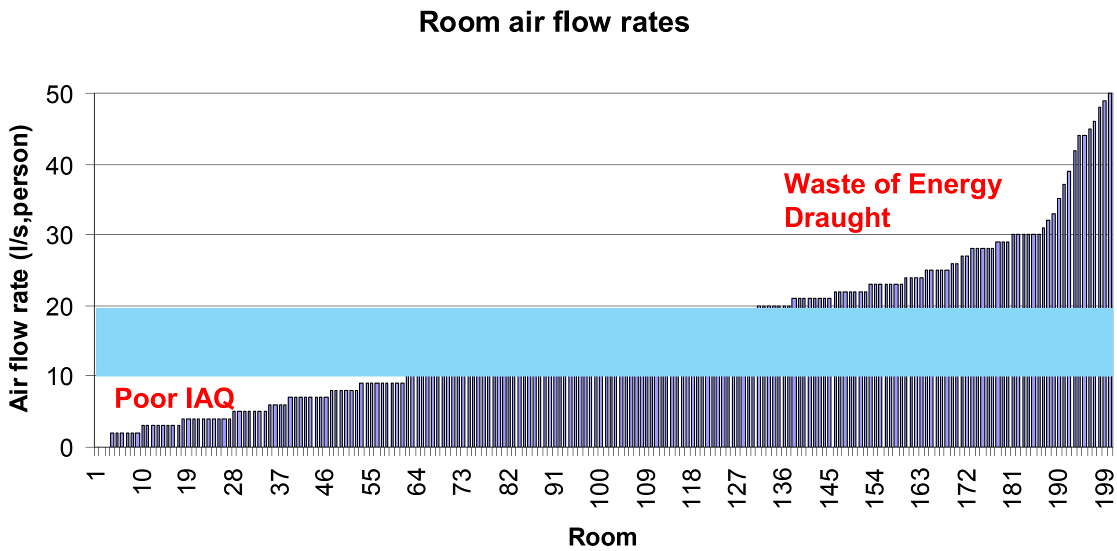

Figure 6. By balancing airflow rates both indoor air quality and energy efficiency can be improved.

3 DESIGN CONSIDERATIONS OF SUSTAINABLE VENTILATION AND ROOM AIR CONDITIONING SYSTEM

The energy consumption of building depends on the design of building envelope, selected HVAC-systems and the maintenance of them. Ventilation system is much easier to improve during the refurbishment than elements related to building envelope.

Solar shading is another important issue, where architects can greatly affect the quality of building and it's energy efficiency. This can normally be improved also during refurbishment. With good solar shading the cooling requirement can be reduced close to internal load level e.g. 40 – 80 W/floor-m^2. This also expands the variety of HVAC-systems, which can be used in building. Low temperature heating and high temperature cooling systems (like slab cooling, chilled ceiling and chilled beams) can be used in such a buildings. Also full-air systems, like displacement ventilation, become more feasible.

3.1 Natural or Mechanical Ventilation System

Natural ventilation is often considered to be the most energy efficient and it is a part of passive building design. However this strategy is often difficult in refurbishment projects. Passive design approach should always involve at' least the use of daylight and high thermal mass as well as utilisation and prevention of solar radiation depending on season. Natural ventilation design should not be considered in isolation from these other design factors and atria and chimneys are often part of system, which are often difficult to modify in refurbishment. However it may be more energy efficient and comfortable to combine natural and mechanical ventilation. There is currently a great deal of speculation and innovation in the design of such 'hybrid' ventilation systems.

Natural ventilation design is often seen as a system providing a high level of occupant control. However users will experience greater variation and extremes of environmental conditions. System does not use fans, therefore is potentially a low energy solution but it cannot incorporate heat recovery, therefore may incur an energy penalty if high ventilation rates are required. Natural ventilation system can have low capital cost due to reduced HVAC-equipment, unless an atrium, or chimneys are needed as part of the ventilation system. In refurbishment projects natural ventilation can be considered only if there is an atrium or equivalent air path to create chimney effect into the building.

Natural ventilation will only be acceptable if the external air quality is good. It is not possible to filter incoming air in a natural ventilation system because the relatively low-pressure differentials will not be sufficient to draw air through the high resistance associated with most types of filters.

3.2 Design of Energy Efficient Mechanical Ventilation System

Mechanical ventilation design provides a controlled environment and constant conditions. It will ensure high ventilation rates in cases of high occupancy or high heat gains. Mechanical ventilation uses energy to circulate air, but fan power can be reduced by good design. The specific fan power (SFP) describes the overall system efficiency. The SFP is defined as the installed motor power (kW) of all fans in the air distribution system, divided by the airflow rate (m3/s). An efficient system has a low SFP (<2,5).

Another important design issue is the overall system pressure drop. Choosing low-pressure air handling unit and low duct velocity (< 4 m/s), the system pressure can be decreased. This typically also improves the sound performance of system.

In constant pressure zones, the unitary airflow rate adjustment does not affect the airflow rates of other terminal units. The commissioning can be implemented very effectively. Even constant airflow rates of office rooms can be integrated into the same ductwork as variable airflow rate control for meeting rooms.

Heat recovery improves energy efficiency and outdoor air filtration improves indoor air quality. Mechanical ventilation enables the design of deep plan or complex spaces.

3.3 Selection Between Various Room Air Conditioning Systems: Case Study

In most of the cases ventilation itself is not sufficient to keep room conditions in desired level. This is why in most of the cases to room air conditioning is also needed. When room air condition strategy is decided, it is important to consider both indoor environmental quality and the energy usage.

This is a case study of an office building located in Paris, France. Maximum outdoor temperature is +28°C. The total area of the building is 6700 m² and the volume 24000 m³. The U-values of the exterior wall and ground floor (against ground) are 0.33 W/m²K and roof 0.21 W/m²K. Windows are triple glazed selective windows without blinds with U-value of 1.37 W/m²K. Internal loads are following: 1 person per 10 m2, lights 15 W/m2, machines 15 W/m2. The air conditioning and ventilation system works from Monday to Friday 07-18, heating operates 24/7. Meeting rooms are fully occupied 5 hours a day (people + machinery). There is a heat recovery is in air handling unit but no night ventilation or any other kind of free cooling. The design temperatures are 24°C in summer and 21°C in winter and the operation temperatures are 23°C in summer and 21°C in winter.

Fan coil system and chilled beam system operates with constant airflow both in offices and meeting rooms. The annual energy consumption varies between systems (Fig. 7). The total energy consumption of fan coil system is highest. The lowest energy consumption is achieved when chilled beam system with constant airflow rates in offices are combined with variable airflow rates in meeting rooms.

	Heating (kWh/m²)	Cooling (kWh/m²)	Fan electricity (kWh/m²)	TOTAL (kWh/m²)
Fan coil (dry)	**31**	**10**	**19**	**60**
Chilled beam	**31**	**9**	**12**	**52**
VAV	**24**	**6**	**11**	**41**
Chilled beams in offices, VAV in meeting rooms	**23**	**8**	**9**	**40**

Figure 7. In this case study the lowest energy consumption is achieved by combining chilled beam system with constant airflow rates in offices with variable airflow system in meeting rooms.

This case study shows, that in terms of energy efficiency it is recommended to control airflow rates based on demand. System efficiency could be further improved by introducing demand-based control also to office areas.

In demand controlled ventilation the energy efficiency of ventilation is improved by controlling the supply air volume according the need. This can be accomplished through varying the ventilation airflow rate based on room air temperature, CO_2 or occupancy. CO_2-sensors are useful in buildings, where occupancy is widely varying e.g. in meeting rooms. Passive infrared sensors can be used to switch off the system, when rooms are not occupied. It is also important to have correct set values in control system to avoid cooling and heating when it is not necessary.

3.4 Terminal Unit Selection in Terms of Good Indoor Conditions and Energy Efficiency: Case Chilled Beams

It is also very important how to select not only the right system concept but also how to select terminal units for project. Following case study shows the importance of chilled beam selection in terms of indoor climate conditions and energy efficiency.

Chilled beam technology is seen as a very sustainable technology providing both excellent indoor conditions but also an energy efficient lifetime. And this is a case with a good design. But if the system is pushed to operate outside the optimum operation area, there is a negative impact in both energy efficiency and user comfort.

A typical design principle is to maximise the cooling output of system per floor area. This typically means long beams (3…3,5 m at 3 m distance) with high water flow rate (e.g. 0,1 kg/s) and chamber pressure (120…150 Pa). This kind of design provides cooling about 120…140 W/m^2. In these cases the maximum room air velocity is about 0,25 m/s and supply air jet temperature is a. 1 ^{O}C colder than room air temperature. (Fig. 8)

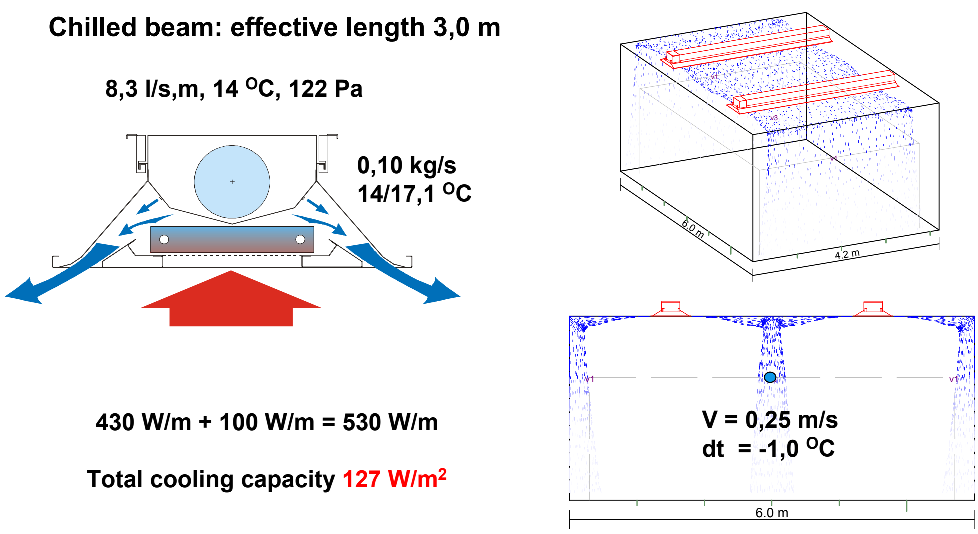

Figure 8. Typical chilled beam design to maximise cooling per floor area.

If the building have a better solar shading, better external structures and dynamic simulation programs are used to specify the required cooling capacity, it is normally enough to have cooling only 60…80 W/m^2. This means that much lower chamber pressure (60…80Pa) and water flow rate (e.g. 0,03 kg/s) can be used. This results much better energy efficiency and also better comfort (room air velocity a. 0,2 m/s). (Fig. 9)

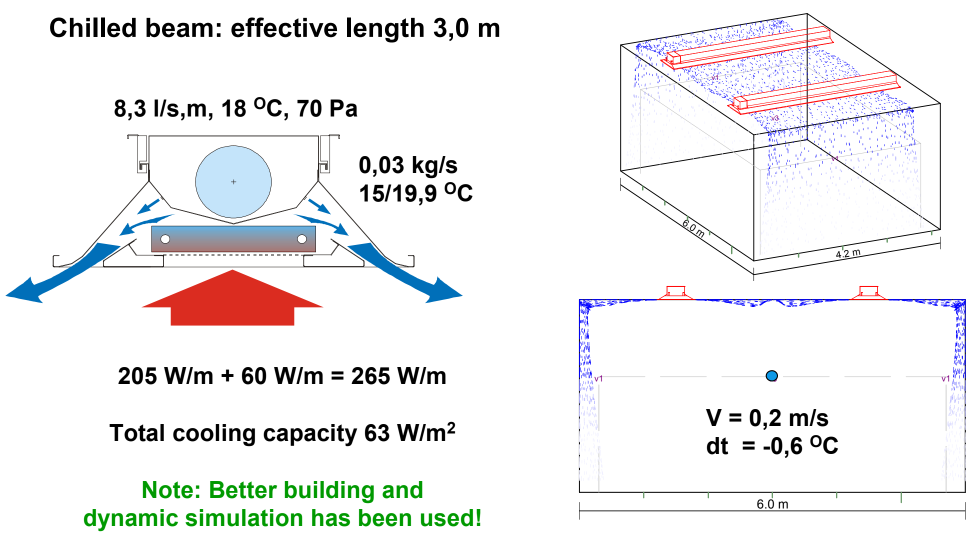

Figure 9. Example of a sustainable chilled beam selection with improved energy efficiency (lower pumping and fan energy) and improved comfort conditions (room air velocity from 0,25 to 0,2 m/s).

If the main purpose is just to minimise unit investment cost, there is a high risk of both increasing the energy use of system and reducing comfort conditions. Shorter beams means normally much higher chamber pressure (150…300 Pa), high water flow rates (e.g. 0,1 m/s) and very high linear primary air volumes (15…25 l/s,m). This gives very high linear cooling capacities (600…1000 W/m), but ends up also to high room air velocity (up to 0,5 m/s) and higher energy use (fan and pumping energy). (Fig. 10)

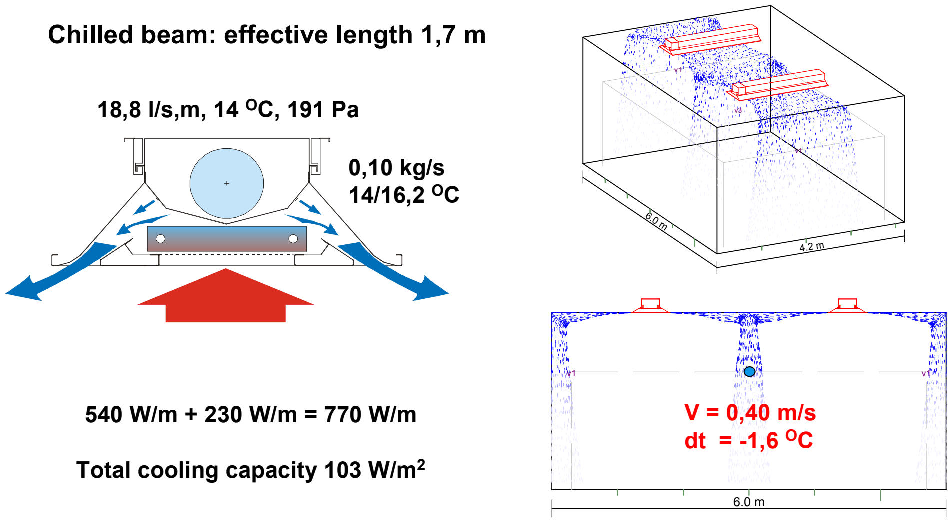

Figure 10. Minimising investment costs means shorter units but higher energy use and reduced comfort in occupied zone.

4 ADJUSTMENT OF TERMINAL UNITS DURING LIFETIME OF BUILDING

Indoor environment is actually not created, until people move in, decide how to use spaces and furnish them. Only then the ventilation terminal units should be adjusted to their final operation point. Final result can be verified based on the human experience of indoor climate.

In design and product selection phase it is also important to pay attention not only to system and product operation in single operating points (e.g. cellular office in maximum cooling and maximum heating), but also analyse the operation in various usage situations (e.g. intermediate seasons, open plan office and meeting room operation).

In order to be able to manage indoor environment efficiently through the lifetime of building, it also requires changes in terminal unit operation. New features in terminal units are needed to enable both easy changes in operation point and also good indoor conditions in varying circumstances.

Designing and selecting terminal units in traditional way allows indoor climate target to be met in the design conditions, but future changes in use or layout may influence the performance of products. This strategy results in lowest possible investment cost, but changes during operation are costly and often requires a project to select new operation points for terminal units.

5 DISCUSSION

In the future refurbishment projects there are a clear need to improve both the energy efficiency of buildings and occupant wellbeing inside the buildings. As shown in this paper this can be done; also in the same building at the same time. However this requires both new technologies and new business models. It also requires a holistic view of understanding the overall challenge. It is easy to save energy by stopping all mechanical systems in the building. This way we quickly generate another problem – users are suffering inside.

This challenges our industry not only to search easy solutions for energy saving or human wellbeing but solving these both challenges at once utilizing new innovations both in technology and processes.

Good indoor climate can be achieved with less energy by selecting such a room systems which allows optimisation of energy efficient cooling and heating.

During construction process the main focus is in good installation and especially in commissioning.

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