Communicating the Acoustic Performance of Innovative HVAC Solutions

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Abstract. Recent years have seen considerable advancements in Demand Controlled Ventilation (DCV) systems aimed to improved energy efficiency and indoor environmental quality in buildings. A significant aspect of DCV systems is their impact on the acoustic comfort in buildings. This study is part of the Urban Tranquility project with a focus on innovative DCV systems. The objective is to add more understanding about communicating the acoustic performance of innovative HVAC solutions during the diffusion phase of the innovation. The research method is a case study on an innovative DCV system that shows how the acoustic performance of the system is communicated with the stakeholders and in what ways the applied methods can be improved. Data collection has been performed through reviewing relevant technical documents and software as well as semi-structured interviews with different stakeholders. The data has been analyzed with reference to three types of knowledge about an innovation. The results indicate that the acoustic performance of this new DCV system has not been effectively communicated due to inconsistent methods of expressing the information. This has revealed the need for developing a systematic method of communicating the acoustic information on DCV systems with the key stakeholders.

Keywords: Innovation, Knowledge, Acoustic information, Demand Controlled Ventilation (DCV), Indoor environmental quality.

1 Introduction

According to the World Health Organization (WHO), exposure to high noise levels harms human health causing sleep disturbance, cardiovascular, and psychophysiological problems [1]. In 2014, environmental noise was reported as the primary cause for hospitalization of 43,000 Europeans annually [2]. Such problems can be more severe in dense urban areas without appropriate plans. According to the Vision Sweden 2025 [3], urban densification has been adopted as a development strategy in Sweden. Noise and vibration (N&V) issues are emphasized as the environmental aspects which must be considered by different stakeholders during the planning and implementation processes of urban densification. Sound insulation in building envelopes can be used as a barrier against outdoor noise in dense urban areas [4]. However, this solution cannot be efficient without sufficient levels of indoor air quality. It means, stale indoor air may prompt users to open the windows for natural ventilation which would expose them to the outdoor noise, rendering the sound barrier useless. Therefore, reliable HVAC systems are needed to provide acceptable levels of indoor air quality and avoid the need for additional ventilation. Moreover, an HVAC system itself can be a source of N&V problems in the building. Thus, innovative HVAC solutions with holistic approach to indoor environmental quality are needed to deal with these issues.

During recent decades, Demand Controlled Ventilation (DCV) systems have been used to condition the indoor air and reduce the energy consumption in different types of buildings. In a DCV system, supply air flow rate and the associated energy consumption is controlled by the actual demand in the space [4]. Several HVAC manufacturers have adopted different approaches to improve their DCV systems [4, 5] while a few of them have marketed innovative solutions using wireless communication [6, 7]. As any innovation involves some levels of uncertainty, the related knowledge and information communicated with customers influence their decisions on adopting an innovative solution [8, 9]. Rogers [8] classified the knowledge about an innovation into three types. The first type, *awareness-knowledge*, is the information about the existence of an innovation; this may motivate an individual to seek other two types of knowledge; *how-to knowledge* and *principles-knowledge*. How-to knowledge is the information required to use an innovation. Inadequacy of this type of knowledge may result in rejecting an innovation; particularly for more complex innovations. Principles-knowledge is the information on fundamental and theoretical principles which underpins the functioning of an innovation. It is possible to adopt an innovation without principles-knowledge; however, this runs the risk of incorrect use and termination [8]. For example, a customer might stop purchasing a manufacturer's DCV system due to noise problems caused by improper design of a building HVAC system.

The process of decision making depends on the available knowledge and the receiver's perception [10]. Perception of an innovation is the process through which an individual receives and interprets related information. This process is directly affected by selecting and presenting the information as well as the credibility of the source of information [11]. Moreover, sustainable competitive advantage can be achieved by managing the information about how different stakeholders use, or respond to innovations [12]. It is also necessary to differentiate between the stakeholders [13] and distinguish the perception and interests of the key stakeholders [11].

1.1 Research Objective

The research objective is to add more understanding about communicating the acoustic performance of innovative HVAC solutions during the diffusion phase of the innovation. This study is part of the Urban Tranquility research project which aims to explore new approaches to support innovative solutions to N&V problems in dense urban areas [14]. The focus of this paper is to investigate how the acoustic performance of an innovative DCV system is communicated with different stakeholders and how the applied methods can be improved.

2 Research Methods

A new DCV system produced by a company called Company A in this paper has been selected as a case to study. Single case study on innovation is a useful approach to reproduce the existing knowledge beyond its original context and provide supplementary knowledge for creating improvements [15]. The data has been collected through reviewing relevant literature, technical documents, and software as the primary source of information for different stakeholders. In order to study the collected information from a wider perspective, similar information available on two other main manufacturers' websites has been reviewed. These manufacturers are called Company B and Company C in this paper. The collected information has been complemented by conducting semi-structured interviews with the system development director, research and development, product, and marketing managers, sales, laboratory, and control systems engineers, HVAC designers and consultants. The information was collected from April to July 2017. A qualitative analysis has been performed with reference to the aforementioned classification of the information about an innovation into three types of knowledge. The acoustic information has been considered at different levels of offerings including solution and products with regard to the indoor and outdoor noise. The scope of this study is limited to the acoustic information on DCV components in a room including comfort modules, diffusers, and dampers. In order to identify the gaps in the knowledge provided by manufacturers in communicating the innovative products, the analysis has been performed on the information which is freely available to the stakeholders.

3 Three Generations of DCV Systems

As one of the main producers of ventilation systems in Sweden, Company A offers a wide range of HVAC products and solutions. On the company's website, "using innovation as a mindset" has been mentioned as one of the assets that enables the company to meet the customer requirements and to be "The Indoor Climate Company" [16]. The company has four R&D departments in Sweden. To date, three generations of DCV systems have been developed and manufactured in one of these departments.

The company's first DCV system was launched in 2000. Noise reduction was highlighted as an advantage of the product. It was achieved by lowering the air velocities and pressure drops in the system [17]. In 2008, the next-generation of the company's DCV system came on the market. The aim was to simplify the installation and commissioning processes as well as the connection to the air handling unit. Configuring the components in the factory and the cabling in the control system increased the risk of human errors during installation processes and further required corrective actions that were costly and time consuming. Customer complaints arising from such complications prompted Company A to solve the problem. Considering the increasing demand for

DCV systems, the company needed an effective action in order to fulfil the customers' expectations and sustain its competitive advantage. Consequently, a radical change in the control system was decided for the third-generation DCV system. A control system based on radio-frequency identification (RFID) was developed through collaborations with other companies [18].

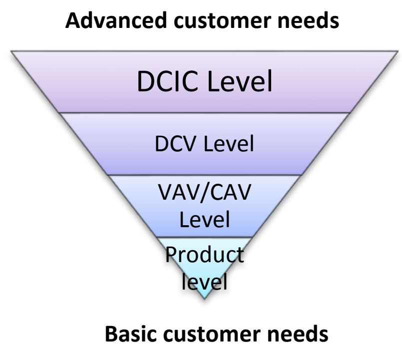

Fig. 1. Different levels of offerings by Company A based on customer needs.

The new system was first introduced at Nordbygg, the construction industry event, in April 2016 and sales processes started in spring 2017. It is named the Demand Controlled Indoor Climate (DCIC) system at the highest level of customer needs, which includes ventilation as well as air and hydronic heating and cooling. The lower levels are DCV, Variable Air Volume (VAV) / Constant Air Volume (CAV), and product [7] (see Fig. 1). The acoustic information about the new system products is provided in the catalogs (in Swedish) available on the company's website [19]. The parameters used to communicate this information are briefly described in the following section.

3.1 HVAC Acoustic Parameters

In HVAC systems, rotating equipment and movement of air and fluids generate vibration and noise. Vibration can radiate noise defined as undesirable sound; noise generated by the air flow is known as airborne noise while structure-borne noise is generated by sources in direct contact with a building structure [20]. Sound is defined as the fluctuations in the atmospheric pressure which can be sensed by our eardrums. It is described by three dimensions as follows: time (s), frequency (Hz), and level (dB) [21]. The latter is used as the unit of both sound power level and sound pressure level, although they are different parameters. Sound power is the sound energy released by a source per unit of time. It is expressed as: $L_w = 10 \log(W/W_{ref})$, where $W_{ref} = 10^{-12}$ Watts [22]. The sound power level of the HVAC equipment is determined by laboratory measurements according to the relevant standards. Sound pressure, in turn, is expressed as $L_p = 20 \log(P/P_{ref})$, where $P_{ref} = 0.00002$ Pa [22]. Sound pressure level can be either measured in a space using a sound level meter or estimated if the space conditions and the sound power level of the equipment are known. Sound pressure level (L_p) can be expressed as a function of the sound power level (L_w) of the equipment and the distance (d) from the equipment to the receiver as:

$$L_P = L_W + 10 \log [4(1 - \alpha)/A + Q/ (4\pi d^2)] \quad (1)$$

where Q is the directivity of the source, α is the mean absorption coefficient, and A is the effective absorption area in square meters [21]. A simple expression of the equation 1 is as follows: $L_P = L_W$ + Room Effect or Attenuation + End Reflection Loss [23]. In Sweden, the acceptable sound pressure level of the HVAC equipment in buildings is legislated by the National Board of Housing, Building and Planning (BBR), which also refers to the sound classes of buildings stated in SS-EN ISO 25267:2015 and SS-EN ISO 25268:2007 standards. Sound levels are specified as frequency-weighted sound pressure levels. Since the sensitivity of the human hearing changes is dependent on the frequency, the sound measurements are weighted as a function of frequency to account for human perception [24]. The maximum A-weighted sound pressure level and equivalent C-weighted sound pressure level are determined for noise from HVAC systems in institutional and commercial buildings [25]. A-weighted sound pressure, in dB(A), is widely used as a single-number measure of the relative loudness of sound. The C-weighted curve, dB(C), is more sensitive to low-frequency sound [21].

4 Results

As inferred from the catalogs [7, 26] and confirmed by the interviewees, the new DCIC system has not been considered as a potential solution to the outdoor noise problems. Therefore, the acoustic information is not highlighted as awareness-knowledge in introducing the system, but rather as how-to knowledge and principles-knowledge at the product level. This means that the innovative solution has been undervalued due to incomplete awareness-knowledge. Hence, this study focuses on the acoustic information of this DCV system's components i.e., products.

At the product level, Company A has different customers amongst whom knowledge of acoustics varies accordingly. According to the interviewees, customer complaints about noise are mainly caused by incorrect applications. Therefore, it is crucial to supply complete principles-knowledge to the designers and consultants as well as appropriate how-to knowledge to the users.

Customers can access the acoustic information about the products through the product data sheets, commercial software, and customized simulations. For special applications, mock-up room tests can be performed upon the customer request. According to the laboratory engineer, the acoustic tests are performed according to the Swedish versions of ISO standards such as SS-EN ISO 3740 series and SS-EN ISO 16032. Nonetheless, such information is not included in the technical documents and software that limits the users' information about the applied measurement methods. Consequently, the presented sound data are difficult to analyze. Moreover, terms, notations and units used in presenting the sound data are not consistent.

Knowing the sound power level of the HVAC equipment, a direct comparison can be made between equipment by different manufacturers; however, the sound pressure levels cannot be determined until the space and the HVAC installations are designed. The sound pressure levels can be used to compare the acoustic quality of two pieces of equipment if the same test conditions are applied [22]. Comparing the acoustic performance of the products is challenging due to inconsistent methods for performing measurements and presenting the results adopted by different manufacturers. Three components of the new DCV system (by Company A) used in a room are the comfort module, the air diffuser and the damper. The challenges of communicating the acoustic performance of those products are discussed in the following.

5 Discussion

The Comfort Module is an induction terminal unit which means it operates without a fan or blower. In the catalog of this integrated heating, cooling and ventilation unit [27], the acoustic data is tabulated for each size of the unit. The equivalent sound pressure levels, in dB(A), are given for different airflow rates based on the nozzle pressure and settings. These values are calculated for a room attenuation of 4 dB (an equivalent sound absorption area of 10 m^2). According to the catalog, calculations for different nozzle settings can be done in two computer programs which will be discussed later.

The term "sound level" is used to express the sound pressure level which can be confused with the sound power level. For each model/size of the product, natural attenuation including end reflection, ΔL (dB), is given in octave bands[1] at different nozzle settings. The sound pressure levels can be converted to sound power levels by using the simplified form of the Equation 1; however, this information is not given in the catalog. Moreover, the information on the applied measurement methods and standards is not provided. Another table shows the weighted sound reduction index, R_w (dB). The values show the airborne sound insulation performance of different types of partition walls and suspended ceilings in a space without the terminal unit and with the terminal unit installed.

A quick selection table on the cover page of the air diffuser catalogue [28] shows the sound pressure levels in dB(A) as a function of the airflow for different sizes of the diffuser. In the catalog, the sound pressure levels, in dB(A), are plotted against the airflow, pressure drop, and throw length. The factor, K_{ok}, and sound attenuations, ΔL, are tabulated for different sizes of the diffuser. The information for calculating sound power levels is confusing as the equation is given twice with both adding and subtracting the factor K_{ok} without any reference to ΔL.

Improvement in the acoustic performance of the new DCV system is not expected by some of our interviewees reasoning that the components are the same as in the previous generation. However, as inferred from the catalogs and confirmed by the R&D

[1] The sound spectrum is divided into eight equal octave bands, each defined by its mid- frequency. The first band is centered on 63 Hz and the eighth band on 8000 Hz.

manager and the laboratory engineer at the factory, the acoustic performance of the air diffuser has improved by nearly 20%. This improvement is worth communicating with internal and external stakeholders.

For the circular damper, the A-weighted sound power level, L_{WA}, is plotted as a function of the air flow rate and pressure drop across the damper at positions from 20% to fully open [29]. The A-weighted sound power level obtained from the diagram, can be converted to the sound power level by adding a correction factor, K_{ok}(dB), tabulated in octave bands. In the same way, the correction factor, K_{trans}, is used to calculate the sound power level transmitted through uninsulated casing. For the rectangular damper, L_{WA} is plotted as a function of air velocity while it is mentioned as the air flow in the text. Furthermore, different notations are used to illustrate the A-weighted sound power levels. The L_{WA} found from the diagram is converted into the sound power level by adding the constant K_{ok}. The correction factor, K_k, is also added to include the effect of the cross section area of the damper.

Reviewing similar data from two other Swedish manufacturers' websites, shows that Company B presents the acoustic data of its circular damper in a similar way for the damper positions limited to fully open and closed. Company C provides a similar diagram without any information about the damper positions and for some models of its dampers, only tabulated values of L_{WA} are given without further information. For the rectangular damper, Company B gives a simplified plot of air velocity against A-weighted sound power level while the tabulated correction factors are given in limited scales. The only information given by Company C is tables of A-weighted sound power levels. It should be noted that A-weighted sound power levels as single numbers are meaningful when applied to sound pressure level values. The single numbers cannot be verified by measurements in the field. Overall, a common method is not adopted by the three reviewed manufacturers to illustrate the acoustic information of their DCV components [4, 30–32].

The software introduced by Company A for selecting the new DCV system products has not been available within the time frame of this study. According to the system guide [26], the sound data can be calculated based on the room type, form, and size. After selecting products in the software, capacity and energy consumption can be calculated in another type of software in order to find the optimum design for the best achievable indoor climate and energy efficiency. In fact, the software features cannot be reviewed until it is put on the market.

According to the terminal unit catalog, calculations for different nozzle settings can be done in the forthcoming software and the one currently available on the company's website. It should be noted that letter "a" has been added as an indicator to the product name in the list of documents on the website [19]; however, it is not mentioned on the catalog cover page [27]. None of these titles can be found in the drop-down menu of products in the current software. Therefore, the user might not be able to perform the calculations due to inaccuracy of the basic information such as the name of the product. This is an example of limited access to the principles-knowledge caused by inaccurate awareness-knowledge at the product level.

6 Conclusions

This paper has investigated the methods used to communicate the acoustic performance of an innovative DCV system with the key stakeholders. The collected information has been analyzed with reference to three types of knowledge about an innovation i.e. awareness-knowledge, how-to knowledge, and principles-knowledge. The results indicate that although the acoustic performance of Company A's new DCV system is a valuable aspect that has been improved throughout the three generations of the system, it has not been emphasized as such in introducing the system by the company. Moreover, the role of the system in benefiting from the sound insulated building envelope against the outdoor noise is neglected. Therefore, the system can be undervalued due to incomplete awareness-knowledge supplied by the company. The inadequacy of this type of information is further reflected in the product selection software, where access to how-to knowledge and principles-knowledge has been limited by inaccurate awareness-knowledge.

Company A's catalogs include acoustic information in the form of diagrams, tables, equations, and short descriptions, which is more informative compared to the acoustic information on DCV systems provided by the other reviewed manufacturers. Nevertheless, the methods used to express the acoustic information are inconsistent and, in some cases, might be difficult to understand. An implication is that improved methods of expressing the data would enable the company to communicate its innovative solution more effectively. Reviewing the acoustic information provided by the other manufacturers shows that they have not followed a uniform method to illustrate the information. In addition, they have occasionally used the A-weighted sound power levels as single numbers, which is not sufficient to evaluate the acoustic performance of a product. Therefore, the available information is inadequate for comparing the acoustic quality of the new DCV products with the other reviewed products.

This study has revealed areas for improvement in communicating the reviewed acoustic information that might apply to the HVAC industry in a wider scope. Firstly, there is a considerable need for a systematic approach focusing on the key stakeholders as the receivers of different types of knowledge. Secondly, standardized terms, notations, and units can be defined based on the terminology used in relevant standards. For example, sound power level appears to be the most applicable parameter for all stakeholders to compare the acoustic performance of the DCV products. More importantly, HVAC designers and consultants need this parameter to estimate the acoustic performance of the equipment in a designed space. Thirdly, citing the applied standards in the technical data sheets can give the acoustics professionals a clear understanding of procedures and influence customers' perception of the innovation by showing credibility of the source of information. In addition, it is necessary to check the documents for errors before publishing and revise them regularly considering the changes in products, standards, and regulations. The findings suggest that a standardized method can be developed by the Swedish Standards Institute for providing the acoustic information by HVAC manufacturers. Further studies are needed to evaluate the quality of acoustic data calculated by the forthcoming software and the impact of RFID wireless communication on the acoustic performance of the new DCV system by performing measurements during the operation phase of the system.

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