DWELLING ENVIRONMENTAL QUALITY INDEX: AN INDICATOR OF INDOOR ENVIRONMENTAL QUALITY IN RESIDENTIAL BUILDINGS

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ABSTRACT

Efforts to save energy may easily lead to the compromisation of indoor environmental conditions and vice-versa. This study suggests an indicator for indoor environmental quality classification, developed with the purpose of assisting households that are trying to save energy, to maintain optimum levels of indoor environmental quality during this effort. The "Dwelling Environmental Quality Index" (DEQI) is a comprehensive indoor environmental quality indicator, reported to occupants as an easily understood number (percentage). The DEQI is calculated for a thermal zone in which indoor air temperature, relative humidity and CO2 levels are monitored. It expresses in a single value the prevalent indoor environment quality category for the monitored period, based on the four indoor environment categories defined in standard EN 15251. Calculations for the DEQI rely on actual hourly measurements which may correspond to an entire-day, a week, a season or to a whole year, and as a result is capable of acting as a performance indicator for short-, medium- and long-term energy conservation measures implemented during the measured period.

KEYWORDS

Indoor environment, quality classification, residential buildings

1 INTRODUCTION

Based on health considerations, and depending on the indoor air quality indicator, acceptable exposure ranges exist for short-term and for long-term exposure (Health Canada, 1995; ASHRAE, 2007). Furthermore, seasonal variations in outdoor environmental conditions cause for relevant changes in the expectations of occupants from their thermal environment and therefore different criteria exist for evaluating the indoor environment during different seasons (CEN 2007b; ISO 2005).
The European Standard EN 15251 (2007b) and ASHRAE Standard 55 (2004) provide guidelines for the measurement of the indoor environment in buildings. In general, it is suggested that measurements are conducted in the spaces where occupants spend most of their time, at a floor height representative of the activity performed in that space. In residential buildings the space in which all occupants commonly spend most of their time is the living room, while activities performed there are mainly sedentary. Therefore, for residential buildings the optimum position for locating sensors is the living room at sedentary head height.
Marino et al. (2012) defined an indoor environmental quality index that can evaluate and classify the indoor environment in both single environments and whole buildings based on numerical values from either actual measurements or from numerical simulations.

This paper presents the application of this environmental quality index in one social housing dwelling in Belgium for a 2 week period in December 2012. This dwelling is one of the (approximately) 300 dwellings from 10 different European countries participating in the EC funded ICE-WISH project. The ICE-WISH project was launched in 2011 with the primary objective of improving energy efficiency in social housing using ICTs, while ensuring that implemented conservation measures will have no adverse influence on the indoor environment. For this purpose the project foresees for the installation of utility meters and sensors for monitoring the indoor environment, namely indoor air temperature, indoor relative humidity and indoor CO_2 concentrations. These three parameters form the indoor environmental parameters used for the evaluation of the dwellings' indoor environment.

2 METHODOLOGY

The proposed methodology allows for the calculation of an indoor environmental quality index that can evaluate and classify the indoor environment in dwellings based on measurements of indoor environmental parameters. It is based on the methodology developed by Marino et al. (2012) for the environmental quality classification of both single environments and whole buildings.

For residential buildings, like in the case of this study, it is considered sufficient to assess conditions in a single zone, namely the living room, where occupants spend most of their time. The methodology is consisting of four main steps. Firstly, the comfort factors and corresponding parameters to be considered in the assessment of indoor environmental quality are identified. Secondly, target values are assigned to each of the comfort parameters. Thirdly, the indoor environmental quality of the dwelling is evaluated through the calculation of the DEQI; and lastly, the dwelling's indoor environment is assigned a comfort class based on the DEQI score.

The first step involves the definition of the comfort factors and parameters to be assessed or, in the case that an assessment has already been performed, the selection of comfort factors and parameters that should be included in the environmental quality assessment. The evaluated period depends on the scope of the study and may be short, like for example a day or week, or longer, like for example a season or a year.

Comfort factors may be from any of the comfort aspects: thermal comfort, visual comfort, acoustic comfort and indoor air quality. Chiang and Lai (2002) and Chan et al. (2008) provide a list of comfort factors and associated parameters that can be included in the DEQI. Indoor air quality for example, may be evaluated through one or more of e.g. suspended particles ($PM_{2.5}$ or PM_{10}), carbon monoxide (CO), carbon dioxide (CO_2), formaldehyde (HCHO) etc.

European Standard EN 15251 (2007b), the Standard that connects energy performance of buildings with indoor environmental input parameters, defines four categories of environmental quality, that can be considered for any comfort factor (Table 1).

Table 1: Environmental quality categories

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons.
II	Normal level of expectation and should be used for new buildings and renovations.
III	An acceptable, moderate level of expectation and may be used for existing buildings.
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year.

The next step, after having identified comfort factors and parameters to include in the evaluation, is to define target values for each of the selected parameters and environmental

quality categories. The target values may differ from one study to another depending on the specifics of the zone under study (e.g. sensitivity of the occupants or of the space to specific parameters).
Next, with the help of the *Time Fraction Matrix [F]*, the time fraction for which hourly values for each of the studied parameters and for the study period expected, fall within each of the four quality categories, is determined.

$$F = \begin{matrix} f_{1,I} & f_{1,II} & f_{1,III} & f_{1,IV} \\ f_{2,I} & f_{2,II} & f_{2,III} & f_{2,IV} \\ f_{3,I} & f_{3,II} & f_{3,III} & f_{3,IV} \\ \dots & \dots & \dots & \dots \\ f_{n,I} & f_{n,II} & f_{n,III} & f_{n,IV} \end{matrix} \qquad (1)$$

with $\sum_{j=I}^{IV} f_{i,j} = 1$

This matrix is made up of as many rows as the number of selected parameters and of four columns (the number of quality categories), with the generic matrix element $f_{i,j}$ representing the fraction of time for which the values of parameter *i* are in the ranges of quality category *j*.
Depending on the priorities and scope of each study, one might want to assign specific weights to each studied comfort parameter. Weighting is incorporated in the calculations for the DEQI through the *Relative Weight Vector {w}:*

$$w = \begin{matrix} w_1 \\ w_2 \\ w_3 \\ \dots \\ w_n \end{matrix} \qquad (2)$$

Ways of obtaining the weighting value for each parameter include the Analytical Hierarchy Process (AHP) (Chiang and Lai, 2002) or through the calculation of a relative weight (Marino et al. 2012).
The multiplication of the *Time Fraction Matrix transpose* $[F]^T$ with the *Relative Weight Vector {w}* produces the *Time Fraction Weighted Mean Vector {f}:*

$$f = F^T w = \begin{matrix} f_I \\ f_{II} \\ f_{III} \\ f_{IV} \end{matrix} \qquad (3)$$

with the generic vector element f_j indicating the persistence of the indoor environmental conditions in the j_{th} quality category.
Finally, the DEQI is calculated through the following relationship:

$$DEQI = 100f_I + 70f_{II} + 35f_{III} + 0f_{IV} \qquad (4)$$

The scores of the DEQI may range from 0, when all values for the measured parameters fall in quality category IV, to 100, when all values for the measured parameters fall in quality category I. In a similar manner, when all values fall in Category II or III, the DEQI results to a

score of 70 or 35, respectively. Overall, the higher the DEQI score the better the overall indoor environmental conditions were in the dwelling for the period of time studied.
Marino et al. (2012) also adapted the energy performance classification of buildings described in European Standard EN 15217 (2007a) according to the definition of the environmental quality categories in EN 15251 (2007b) to establish a seven point scale (scale A to G) classification of the indoor environment as shown in the Table 2.

Table 2: DEQI results for each of the studied periods

DEQI	Indoor Environment Quality Class
90-100	A
75-90	B
60-75	C
45-60	D
30-45	E
15-30	F
0-15	G

The idea behind this is that the higher the DEQI score, the closer the indoor environmental quality is to the optimum class A.

3 APPLICATION OF THE DEQI IN AN ACTUAL DWELLING

The methodology presented earlier was adapted to the needs of the ICE-WISH project. This section presents the application of a preliminary version of the DEQI in a dwelling in Belgium.

3.1 The application environment

The dwelling studied here is an apartment in a social housing block located in Genk, Belgium and it is one of the 30 dwellings participating in ICE-WISH from the specific pilot. The total floor area of the dwelling is 43.26m^2 and it is comprised of 5 spaces: living/dining room, bedroom, kitchen, bathroom and a corridor. The floor plan of the apartment is presented in Figure 1. The building was constructed between 1965-1975 and was fully renovated in 2006. After the renovation individual condensing gas-boilers were installed in all apartments used for space heating and domestic hot water, and the thermal performance of the envelope was also significantly improved (with additional insulation and installation of high performance window systems with ventilation grids). Fresh air is supplied through the ventilation grids to the living room and bedroom while a ventilation shaft in the bathroom, kitchen and toilet provides exhaust ventilation. The apartment is occupied by one person. The structure presents no issues with condensation or mould.

Figure 1: Test dwelling

For the purposes of the project utility meters were installed for the measurement of total energy and water consumption and sensors for monitoring the indoor environment, namely indoor air temperature, indoor relative humidity and indoor CO_2 concentrations were installed in the living room. These three parameters will form the environmental parameters studied in the application of the DEQI in this section.
The measurement data used in this study are in hourly intervals and correspond to two consecutive weeks in December of 2012. The comfort factors considered in the study along with the corresponding parameters are listed in Table 2.

Table 2: Comfort factors and corresponding representative parameters

Comfort factors	**Representative parameters**
Winter thermal conditions	Indoor Temperature (^oC)
	Relative Humidity (%)
Air Quality	CO_2 concentrations (ppm)

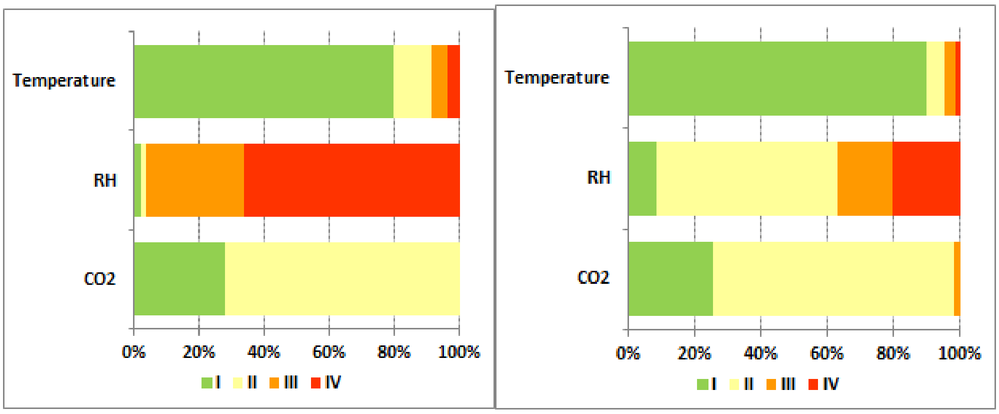
Because this is a preliminary study to validate the basic concept of the DEQI, all measured comfort parameters were assigned with the same weighting.
The target values for the monitored environmental parameters are presented in Table 3.

Table 3: Parameters values for the four environmental categories for winter

Parameter	**Environmental quality category**			
	I	**II**	**II**	**IV**
Indoor Temperature (^oC)	21-25	20-21 25-25.5	18-20 25.5-26	<18 >26
Relative Humidity (%)	35-50	30-35 50-60	25-30 60-70	>70 <25
CO_2 concentrations (ppm)	<600	600-1000	1000-1500	>1500

3.2 Results

The time fraction matrix for weeks 1 and 2 and as a total for the two weeks, respectively, is presented in a graphical manner in Figure 2 and Figure 3. It is calculated through Equation 1.



(a) (b)

Figure 2: Time Fraction matrix for a) week 1 and b) for week 2

As pointed out from the results, temperature is at optimum levels (Category I) for the majority of time for both weeks. CO_2 levels are at normal levels for a renovated building (Category II) for the majority of time and at optimum levels for part of the time also. Relative humidity in week 1 had an average value of 24%. This is clearly illustrated in Figure 2a where Relative Humidity is below the moderate level (Category IV) for the majority of time. In week 2, Relative Humidity levels are slightly improved (weekly average is 30%) and this is also clearly illustrated in Figure 2b.

Figure 3 gives the time fraction matrix for weeks 1 and 2 combined. Temperature and CO_2 levels do not differ significantly from the individual values for weeks 1 and 2 shown in Figure 2. Contrarily, the distribution of Relative Humidity hourly values in the four environmental quality categories differs significantly between weeks 1 and 2 combined and individual weeks. This is because Relative Humidity is so different between weeks 1 and 2, that even the average of these two cases (weeks 1 and 2 combined) differs importantly from conditions in individual weeks (weeks 1 and 2, individually).

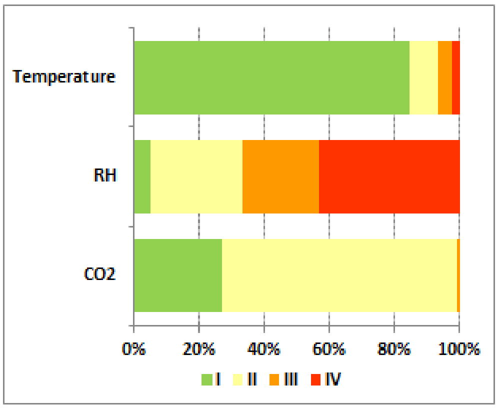


Figure 3: Time Fraction matrix for weeks 1 and 2 combined

What is important to notice here is that if one would study only week 1 (Figure 2a only), then the immediate conclusion would be that the dwelling has a significant Relative Humidity issue, while if week 2 was studied independently (Figure 2b only), then conclusions for temperature and CO2 levels would be similar to those of week 1, but conclusion for Relative Humidity would be that for a significant amount of time Relative Humidity is at normal levels of expectation. The study of the biweekly results on the other hand would give a more representative picture of the dwelling’s conditions as it covers both periods of time (week 1 and week 2). Since the calculated biweekly values are the average of the two individual weeks they would show an intermediate condition between normal (week 2) and rather unacceptable (week 1) for Relative Humidity.

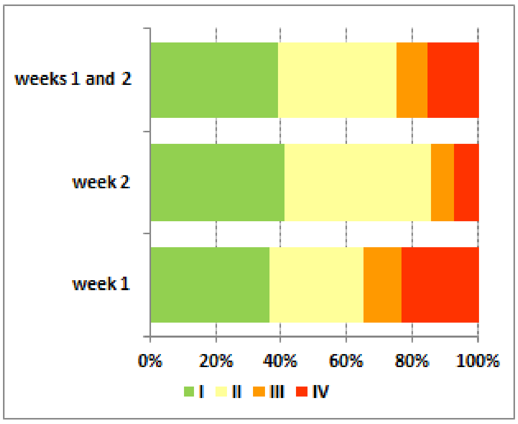


Figure 4: Time Fraction Weighted mean vectors for all studied periods

Figure 4, enhances the value of this observation by showing the overall impact that the variation in one single parameter (in our case that of Relative Humidity) can have on the Time Fraction Weighted mean vectors. It is calculated with the help of Equation 3. In addition, the same Figure also suggests the importance of a DEQI evaluating the indoor environment at a short-term (weeks 1 and week 2 individually) and at longer-term (weeks 1 and 2 combined), since the combined results show that the dwelling is not performing neither as bad as noticed for week 1 nor as good as noticed for week 2. However, both cases, the short-term and longer-term have their importance. The short-term helps the user to focus on the problems better, while the longer-term gives the bigger and more representative picture of indoor environmental conditions.

Next, the DEQI is determined, with the help of Equation 4. Results are presented in Table 4. As shown, during week one the DEQI score is 61 and very close to quality class D, while during week 2 the DEQI is at the boundary between class B and C. Looking at the 2 weeks combined the DEQI is at the middle of class C and the value of the DEQI is the average of the DEQI score for week 1 and 2, respectively.

Table 4: DEQI results for each of the studied periods

Study period	**DEQI**	**Indoor Environment Quality Class**
Week 1	61	C
Week 2	75	C
Weeks 1 and 2	68	C

4 CONCLUSIONS

The Dwelling Environmental Quality Index is able to communicate to occupants a large and significant amount of information regarding their indoor environmental conditions in a single value.

When the DEQI is calculated for a short period of time (i.e. a day or a week) it can assist in the identification of activities that affect the indoor environment in a positive or negative manner. It can also help occupants stay updated and even set short-term targets for the improvement of the quality of their indoor environment.

When considering measured values for a longer period of time the DEQI provides a more objective overview of the indoor environment as it helps mitigate the effects on the indoor environment of casual activities or events taking place inside or outside the dwelling in the short-term.

When only a small number of environmental parameters is considered in the DEQI then the impact that each of the parameters may have on the DEQI score is significant. On the other hand when a large number of parameters are considered in the DEQI then the impact of individual parameters on the DEQI is less profound. This also shows how important and delicate the matter of assigning weighting factors to each environmental parameter included in the DEQI calculations can be. Especially when occupants or the building structure have problems that are impacted by specific parameters (i.e. humidity, temperature etc) extra care should be put in the weighting assignment.

The individual study of parameters considered in the DEQI is important for understanding the impact that each parameter has had on the final DEQI score and consequently the areas where occupants should focus their efforts for improving their indoor environment, but also the areas were no additional or significant effort is necessary.

Finally, the DEQI can prove to be a very useful tool for occupants that receive energy consumption feedback at the same frequency as they receive the DEQI score. Just by comparing the DEQI score to the percentage of energy savings for e.g. one day or one week to the day or week before, respectively, one can determine whether energy savings were compromised in favour of better environmental conditions, or vice versa. In time, the comparison of the two values (% savings and DEQI score) could help occupants become more aware of the interactions between energy consumption and the indoor environment in their home and as a result help them find the balance that they prefer for their own home between the two.

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