Is the air change efficiency sufficient to assess the removal of airborne contamination in mixing ventilation?

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ABSTRACT

This investigation analyze the correlation between two common methods to assess the ventilation effectiveness: An averaged contamination removal effectiveness (CRE) value based on the residual lifetime and the air change efficiency (ACE) to better understand their relationship to then give a recommendation for the IAQ-assessment of ventilation designs.

The present numerical investigation puts focus on a simple mixing ventilation scenario with different conditions: air change rate, specific heat flux, supply air diffuser and exhaust position. Statistically, the results show a significant correlation. A detailed consideration, especially for the partial load range, will be necessary to for a valide determination of removing airborne contamination.

INTRODUCTION

There are two common methods to assess ventilation effectiveness: the air change efficiency and the contamination removal effectiveness . For known contamination sources in a room, it is easy to determine the CRE. Often the source position is unknown or too variable. Especially, when the contamination is exhaled from a random position and gets mixed up in the environment. Then the ACE, the ability of the ventilation to exchange the air in the room, should be used for Indoor Air Quality (IAQ) assessment.

By determining the residual lifetime, the averaged time for air transport from a specific point in the room to the exhaust, it is possible to examine the resulting CRE and ensure, if the point is the source position and the contamination is airborne. This data can be averaged for the whole room or a potential source zone.

The Air Change Efficiency ε is the quotient of the nominal time constant (Equation 1) times 0.5 and the averaged age of air in the room (Equation 2).

$$- \quad - \qquad (1)$$

$$\overline{} \qquad (2)$$

Under the current pandemic circumstances, the focus of common ventilation shifts to airborne viruses and how long the infectious aerosols linger in the room. In order to determine the air quality in rooms with known sources of pollution, pollutant removal parameters are suitable. The Contaminant Removal Effectiveness ε^c is described by Equation (3). It is the quotient of the difference between the pollutant concentration in the exhaust c_{ea} and supply air c and the difference between the average concentration in the room c and the supply air.

$$(3)$$

The CRE is limited to a single pollutant and source distribution, but a real room has multiple and/ or undefined pollutants. Each emanating from a different location, none of which can be predicted. This results in the general recommendation, to use the ACE for general indication of air quality independently of contaminant source positions (Mundt et al. 2004; Novoselac and Srebic 2003). This gives the rise to the question of how much the air exchange efficiency is sufficient to assess the removal of airborne contamination? (Fisk et al. 1997) show a strong correlation for the ACE and the pollutant removal efficiency for a passive, spatially-distributed source on the floor. For a second source, body-odor pollutant, no correlation could be found. (Novoselac and Srebic 2003) show the correlation of ACE and CRE for different source locations (floor, wall, occupants) and ventilation strategies (mixing – and displacement ventilation). For mixing ventilation the correlation is strong and differences between the source positions are not significant.

In this study the correlation between ACE and CRE should be approved by a numerical analysis considering different mixing ventilation parameters:

- air change rate n,
- temperature difference between exhaust and supply air $\Delta T = T_{ea} - T_{sa}$,
- supply air diffuser (swirl and slot) and
- exhaust positioning.

METHODS

Numerical Model

A 3D model with the CFD software STAR-CCM+ is used. The room has a height of 2.9 m and a floor area of 5.2 m x 4.4 m. Two different supply air diffuser a swirl inlet at the ceiling center and a wall slot diffuser are implemented. Different exhaust air positions are investigated; for the slot diffuser five different exhaust openings (ea1 - ea5) and the swirl diffuser two symmetric (ea12 and ea34) and two asymmetric exhaust configurations (ea1 and ea4) (see Figure 1).

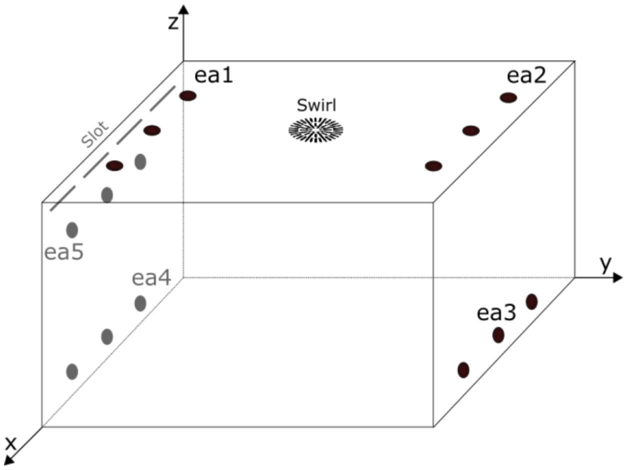

Figure 1. The geometry of the investigated room with the supply air and exhaust openings

Table 1 shows a summary of the mesh, boundary, and solver settings. The different parameter setups of the supply air can be seen in Figure 2.

Table 1. Boundary conditions and settings CFD model

Supply air	Inlet, Q = 25 ... 500 m³/h, = 291.15 K
Exhaust	Outlet
Floor, Ceiling, Walls	Adiabatic
Dummies	P = 0 ... 500 W
Turbulence model	RANS, Reynolds Stress Turbulence Model (Elliptic Blending)
Physics	Ideal Gas, Gravity, Radiation (surface-to-surface)

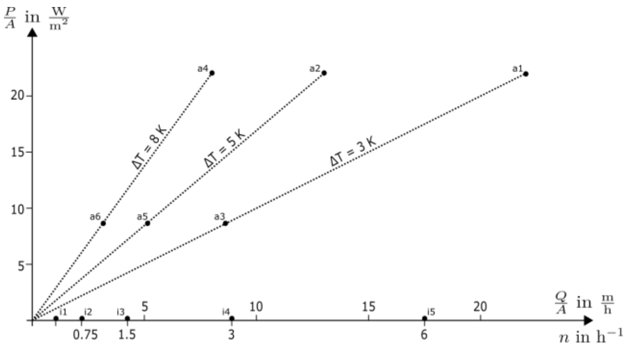

Figure 2: Parameter setups for the supply air

Ventilation Effectiveness

The air change efficiency can also be determined for a single point in the room – it is called the local air change index ε_p^a (Equation 4).

— (4)

Additionally, CRE can also be obtained by (Equation 5). It based on the turnover time τ_t^c, the averaged time needed to remove the contaminant and put it in relation to the nominal time constant.

— (5)

Besides the age of air (Sandberg and Sjöberg 1983) introduced the residual lifetime (see Figure 3). Residual lifetime is the mean residence time of air from any point in the room till it leaves the room through the exhaust. Assuming ideally airborne contamination it corresponds to the turnover time for every possible source position. Thus, a resulting CRE can be calculated for every hypothetical source position. The numerical method to determine the residual lifetime is a reversed CFD-simulation first used by(Kato et al. 1993).

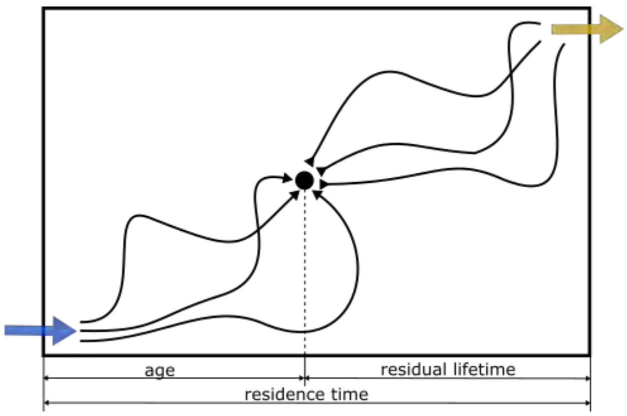

Figure 3. Definition of different ages (based on Sandberg and Sjöberg 1983)

In this investigation the focus is on the local air quality index and the contaminant removal effectiveness. For the assessment a grid of 40 x 48 points on 18 horizontal planes (total 34560 points) is set in the breathing zone (BZ). A limitation of the breathing zone counteracts extreme values at the room boundaries, e.g. directly at the air diffusers. The BZ is defined by (ASHRAE 2010) as the innerspace between a height of 0.075 m and 1.8 m and a distance of 0.6 m from the surrounding walls. Each of the two quantities ACE and CRE is summarized in a single value - the median. The median and not the mean value is chosen because the standard deviations of the CRE are too high and a robust value is needed.

Correlation analysis

The most famous correlation coefficient is the Pearson correlation coefficient. This is the covariance (fluctuation of the values around the mean) regarding the maximum oscillation of the individual variables. The Pearson correlation is a measure of linear association. It is between -1 and +1. A value of +1 shows a perfect positive correlation and -1 a perfect negative correlation. If it is 0 the two variables are completely independent. The significance is the probability that the correlation is not an accidental finding (p-value). In this investigation it is fulfilled, when the p-value is smaller than 0.05. In addition to the Pearson correlation, the Spearman correlation is also calculated. The Spearman correlation does not evaluate the linear relationship, but only a general ranking or the monotonicity. Therein lies a crucial advantage: For the study of mixing ventilation it is expected, that the values for ventilation efficiency are close to the efficiency for ideal mixed ventilation. This can lead to a strong linear correlation, which does not necessarily reflect a clear monotonicity. Additionally, a normal distribution of the data points is not a prerequisite for the application of the Spearman correlation. This is not guaranteed depending on the reduction of the data points to certain parameter spaces.

RESULTS

For all selected parameter constellations, the data points are plotted in a diagram and the correlation coefficients and linear regressions are implemented. The linear regression describes the functional relationship between the variables: the median of the contamination removal effectiveness on the y-axis and the median of the local air change indices on the x-axis.

The first figure, Figure 4, shows the complete data set. A significant correlation is visible. The (median) CRE rises with the (median) ACE. At higher values the distance between the data points and the regression increases.

The difference in regression between isothermal and non-isothermal cases is small (see Figure 6). Also, a finer subdivision and on the different supply air parameters mostly show significant correlations (see Table 2). For very small air changes (parameter point i1) the correlation coefficient decreases, and the significance criterion ($p < 0.05$) is not met.

With the differentiation of the supply air diffuser (see Figure 7), it becomes clear that the swirl diffuser achieves a better mixing of the room air. The point cloud is denser around the value of one. The Pearson correlation ($r = 0.7$) is strong, but the Spearman correlation ($r = 0.58$) is significantly smaller.

Separate consideration of the supply air type with the associated exhaust air position (see Table 3), no longer reveals a significant correlation between CRE and ACE for every exhaust position.

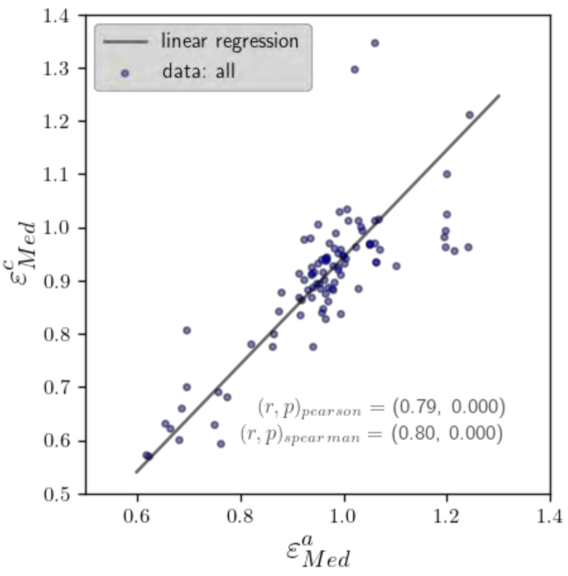

Figure 4. Correlation between the median local air change index and the median contamination removal effectiveness for all cases

DISCUSSION

Generally, the results show a correlation between CRE and ACE. With $r = 0.8$ for all cases. This is significantly lower than the correlation in the investigation from (Fisk et al. 1997) with $r = 0.99$ for a spatially distributed floor source. But it matches very well with the correlation coefficients from the data in (Novoselac and Srebic 2003). If the data is cleansed from the displacement and natural ventilated data points the correlation coefficient is depending on the source (floor, wall and occupants) between 0.7 and 0.9. (Fisk et al. 1997) used the same room setup for all measurements. Only the supply air conditions are changed. (Novoselac and Srebic 2003) compare different rooms and ventilation strategies.

Plotting the residual lifetime above the age of air, the correlation is significantly higher, $r = 0.98$ (see Figure 5). It could be just a scaling effect: a higher residual lifetime comes with higher age of air, because they both depend on the air flux. The plot makes it very clear that the correlation decreases sharply in the partial load range.

The correlations of CRE for individual exhaust positions are worse. Especially, a monotonic relationship can be excluded for most setups (low Spearman correlation). This suggests, that the influence of supply air parameters are more decisive on the correlation.

Through the evaluation of a median CRE value for every possible source position, one would initially expect CRE and ACE to converge strongly. The results show that this is not true. There are enough cases where CRE improves and ACE does not and vice versa. An example is shown with a section plot of the local air change index and the contamination removal effectiveness in Figure 8. The air change efficiency for a swirl diffuser (with an impuls dominant supply air parameter) has a better performance with a lower exhaust position and the contamination removal with an exhaust position at the ceiling.

Further, the local values have significant differences. Plotting the standard deviation for the CRE and ACE values, shows a higher scatter for the CRE values. Which is why the median and not the mean value is used for the evaluation. But also the interquartile range (IQR, difference between 75th and 25th percentiles) is larger by a factor of 10 for the CRE (see Figure 9).

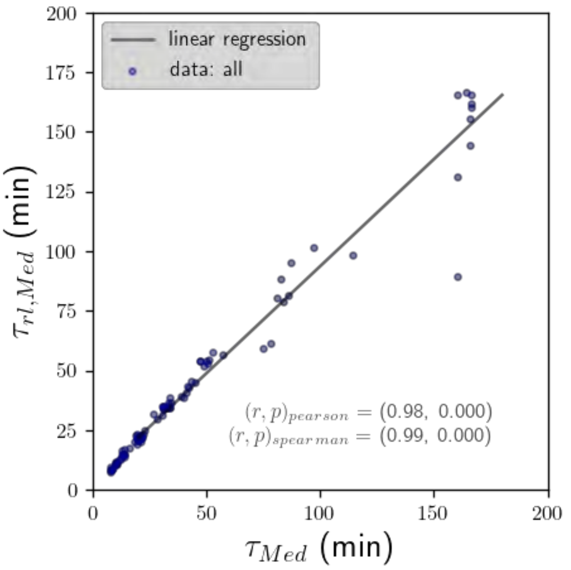

Figure 5. Correlation between the median age of air and the median residual life time against all cases

CONCLUSIONS

The answer to the question, *is the air change efficiency sufficient to assess the removal of airborne contamination in mixing ventilation*, cannot be applied conclusively. Yes, there is a general correlation around r ≈ 0.8, but it doesn't seem to be sufficient, when it is possible to achieve a contamination removal ±20 % for the same air change efficiency. The causalities must be broken down in a more differentiated way in future investigations.

For full load mixing ventilation, an initial estimate of the ventilation effectiveness based on the desired exchange efficiency is legitimate. To reduce airborne infections, allergic reactions, etc., it is necessary to assess the real performance of contamination removal for ventilated spaces. The numerical approach via the residual lifetime is equivalent to the age of air from the source position independently determinable. The additional effort is justifiable for a better IAQ-assessment.

ACKNOWLEDGMENTS

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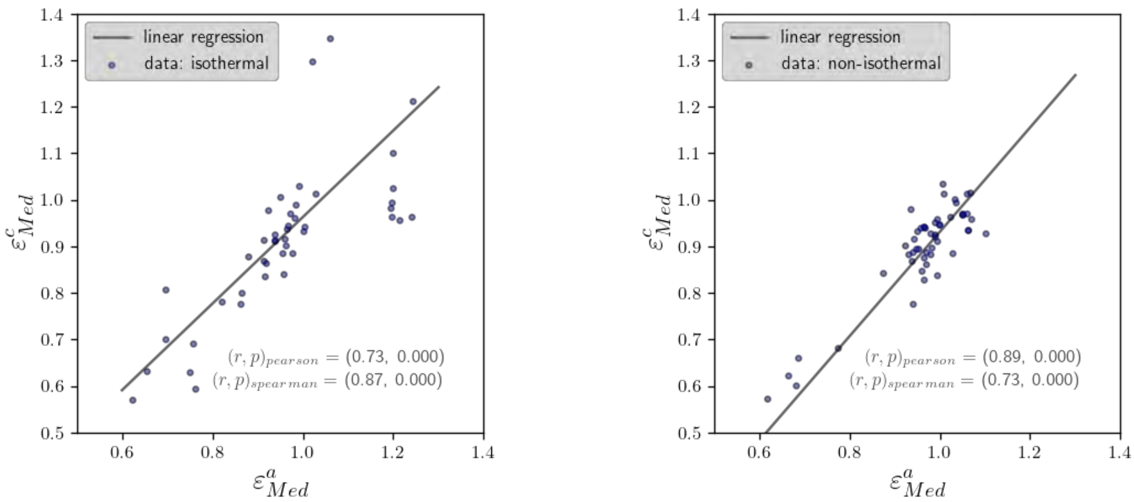

Figure 6. Correlation between the median local air change index and the median contamination removal effectiveness grouped by non- and isothermal cases

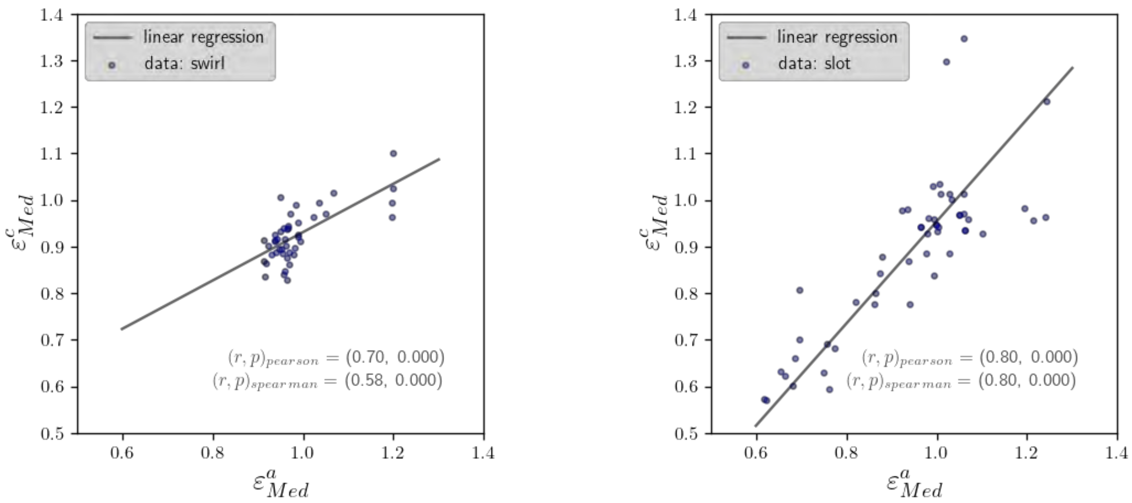

Figure 7. Correlation between the median local air change index and the median contamination removal effectiveness grouped by supply air diffuser

Table 2. Correlation between the median local air change index and the median contamination removal effectiveness grouped by different supply air parameter (non- and isothermal)

Parameter	n	dT	$r_{pearson}$	$p_{pearson}$	$r_{spearman}$	$p_{spearman}$
i5	6.00	0	0.95	0.000	0.85	0.004
i4	3.00	0	0.96	0.000	0.92	0.001
i3	1.50	0	0.97	0.000	0.93	0.000
i2	0.75	0	0.78	0.013	0.90	0.001
i1	0.38	0	0.58	0.098	0.37	0.332
a1	7.57	3	0.96	0.000	0.90	0.001
a2	4.52	5	0.90	0.001	0.58	0.099
a3	3.01	3	0.82	0.006	0.43	0.244
a4	2.83	8	0.92	0.000	0.60	0.088
a5	1.81	5	0.96	0.000	0.80	0.010
a6	1.13	8	0.97	0.000	0.60	0.088

Table 3. Correlation between the median local air change index and the median contamination removal effectiveness grouped by different supply air diffusers (sa) and exhaust positions (ea) (data reduced by parameter i1)

sa	ea	$r_{pearson}$	$p_{pearson}$	$r_{spearman}$	$p_{spearman}$
swirl	ea12	0.85	0.004	0.5	0.356
	ea1	0.72	0.028	0.5	0.170
	ea34	0.82	0.007	0.52	0.154
	ea4	0.26	0.508	0.08	0.831
slot	ea1	-0.24	0.538	-0.14	0.714
	ea2	0.72	0.000	0.55	0.004
	ea3	0.55	0.028	0.49	0.128
	ea4	0.22	0.562	0.39	0.293
	ea5	0.18	0.635	0.33	0.389

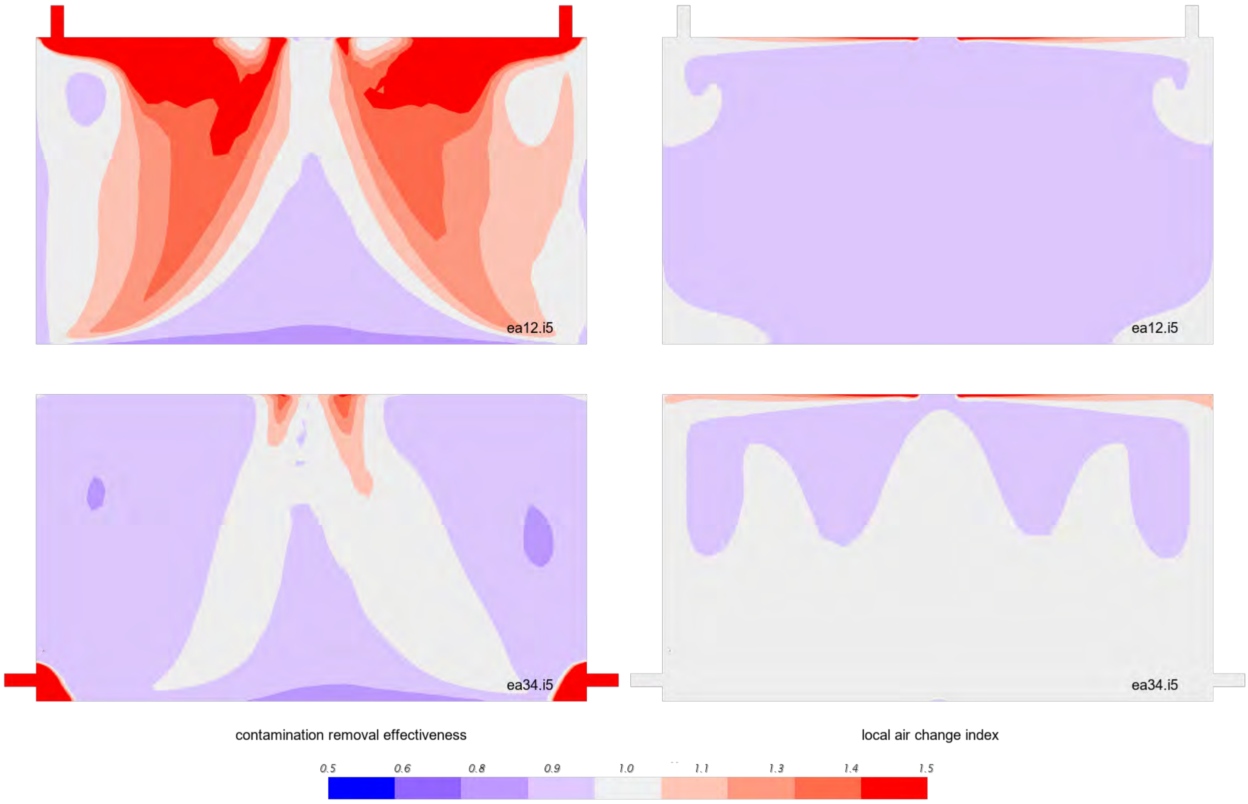

Figure 8. Comparison of the contamination removal effectiveness and the local air change index for two chosen swirl diffuser cases on a plane section (x = 2.2 m)

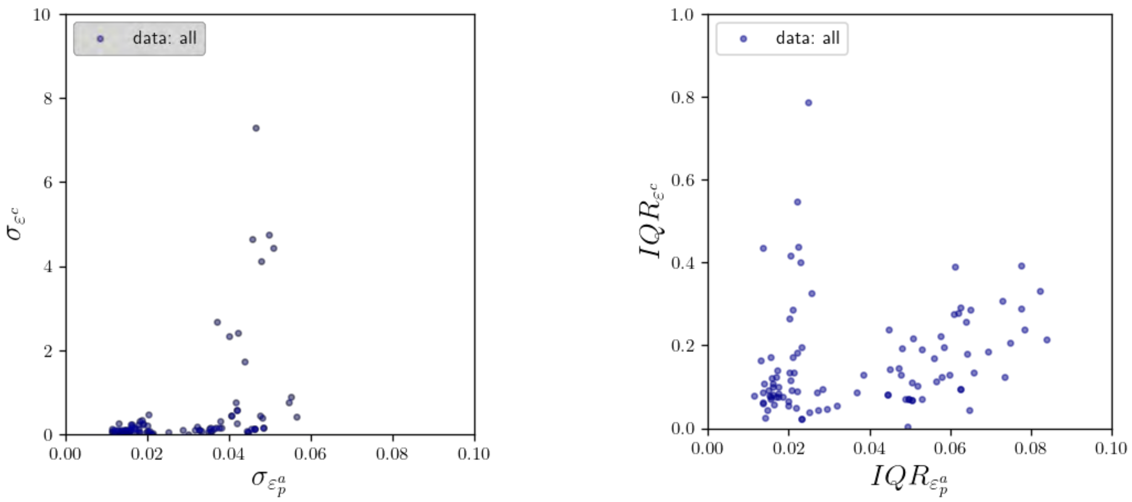

Figure 9. Quantification of the local distribution standard deviation (left) and interquartile range (right) of the ACE and CRE values for all investigated parameters