Sensitive analysis of calculation of corrosion rate according to standard approach

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Abstract. There is a lot of factors, which may affect the reliability of the construction, as durability, serviceability and safety of construction or its parts elements. Corrosion damage either reinforcement is one of the most important factor in reinforced concrete structures or structures made from structural steel. This corrosion damage can be determined by actual standard EN ISO 9223. This standard describe the equations, called dose-response functions, for calculation of the corrosion rate r_{corr} for standard materials like carbon steel, zinc and so on. These equations are determined from the corrosion rate of samples under outdoor atmospheric corrosion in cooperating with measuring of climatic data. Input parameters on calculation of the dose-response functions are sulphur dioxide, temperature, relative humidity and chloride ions. This article is focused on the calculation of the carbon steel corrosion rate according the dose-response function and its sensitive analysis for various concentration of the input parameters. This variability of the input parameters may represents the different conditions, in which the constructions may appears. In practice, this information may provide, which of the input parameter influence the most the calculated corrosion rate and if it is needed to more concentrate its measuring station network. The location of the outdoor stations with the specimens or choice of accelerated corrosion test may be also provided.

1. Introduction

All materials are affected by the surrounding environment [1-2]. It means that the climatic condition and air pollution like temperature, relative humidity, sulphur dioxide, chloride ions etc. may increase or decrease speed of the corrosion rate r_{corr} [3]. Many researches have been done to assess the correlation between corrosion damage (corrosion rate) and aggressiveness of the environment. Nowadays, the standard EN ISO 9223 [4] describe the designation of the yearly corrosion rate for the first year of exposure. The corrosion rate r_{corr} can be designated either on standard specimens under real environment or calculated according to equations so called as dose-response functions. Calculation of these functions is based on the climatic information obtained from the public's hydrometeorogical institutes. The dose-response function for the carbon steel is following:

$$r_{corr} = 1.77 \cdot \left[SO_2 \right]^{0.52} \cdot \exp(0.020 \cdot Rh + f(t)) + 0.102 \cdot \left[Cl^- \right]^{0.62} \cdot \exp(0.033 \cdot Rh + 0.040 \cdot T) \quad (1)$$

where r_{corr} is the corrosion rate (μm/year), f(T) = 0.150·(T – 10) when T≤10°C; otherwise – 0.054·(T – 10), SO₂ is the sulphur dioxide (μg/m³ or mg/(m²·day), where SO₂ in units mg/(m²·day) is equal to 0.8·SO₂ in unit μg/m³), T is the temperature (°C), Rh is the relative humidity (%), Cl⁻ is the chloride deposition rate (mg/(m²·day)). The standard EN ISO 9223 [4] describe the interval of these input parameters, see table 1.

Table 1. Input parameters used in the dose-response functions, including description, symbol, interval, 30 - 70% of these input parameters, mean values and unit.

Description and symbol	Interval	30 – 70 percentage of input parameters	Mean value	Unit
Temperature T	-17.1 – 28.7	-11.97 – 20.09	4.06	˚C
Relative humidity Rh	34 – 93	50.70 – 65.10	57.90	%
Deposition of SO_2	0.7 – 150.4	1.14 – 131.60	66.37	$mg/(m^2 \cdot day)$
Deposition of SO_2	0.6 – 120.3	0.91 – 105.28	56,01	$\mu g.m^{-3}$
Deposition of Cl^-	0.4 – 760.5	0.52 - 532.34	266.44	$mg/(m^2 \cdot day)$

2. Sensitive analysis of dose-response equation for carbon steel

The sensitive analysis may be carry out either when the fixed input parameter is represented by its mean value or the most frequent values, while only one parameter is changed. In this study, for better representation how is the sensitivity of the dose-response function, the range of values of the input parameters were chosen in the range of their interval according the standard EN ISO 9223 [4] and not in the range of maximum or minimum values, which were monitored by the Slovak Republic by Slovak hydrometeorological institute (SHMU) [5]. For this reason, not the frequent but the mean values of input parameters were chosen as the fixed parameters. In addition, various combinations of these fixed input parameter were calculated and its results, as well as the discussion and conclusions were made.

Table 2 shows the changes of input parameters in the ten steps, as well as the calculation of the corrosion rate according equation (1).

Table 2. Changes of input parameters in the sensitive analysis and the calculated corrosion rate r_{corr} of carbon steel according the equation (1).

Percentage of input parameter	Temperature		Relative humidity		Deposition of SO_2		Deposition of Cl^-	
	Changing parameter	r_{corr}	Changing parameter	r_{corr}	Changing parameter	r_{corr}	Changing parameter	r_{corr}
(%)	(˚C)	(μm/year)	(%)	(μm/year)	(mg/(m². .day))	(μm/year)	(mg/(m². .day))	(μm/year)
0	-11.97	15.27	50.70	36.19	1.14	28.07	0.52	18.78
10	-8.76	18.15	52.14	37.64	14.18	34.04	53.70	27.82
20	-5.56	21.92	53.58	39.16	27.23	37.35	106.89	32.92
30	-2.35	26.99	55.02	40.74	40.28	39.94	160.07	37.10
40	0.85	34.03	56.46	42.39	53.32	42.15	213.25	40.77
50	4.06	44.11	57.90	44.11	66.37	44.11	266.44	44.11
60	7.27	58.91	59.34	45.90	79.42	45.89	319.62	47.20
70	10.47	76.77	60.78	47.77	92.46	47.54	372.80	50.10
80	13.68	74.46	62.22	49.72	105.51	49.08	425.98	52.84
90	16.88	73.86	63.66	51.75	118.55	50.53	479.17	55.46
100	20.09	74.90	65.10	53.87	131.60	51.90	532.35	57.97

The sensitive analysis of the dose-response function for carbon steel was calculated on the basis of the following considerations:

- it was suitable to avoid the extreme values of input parameters, for this reason the table 1 describe us chosen interval between 30 % and 70 % of the input parameters,
- all input parameters was fixed in the mean value (see table 1), while only one parameter was changed,

- this parameter was changed in ten steps from its minimum value (represent 0%) to its maximum value (represent 100%), see table 2,
- the procedure described above, where only one parameter was changing while another parameters were fixed in the mean value, was made for all input parameters like temperature, relative humidity, deposition rate of 3ulphur dioxide and chloride, as can be seen in figure 1,
- for better demonstration, the intervals according the standard is described, in the table and graphs, not in the range from 30 to 70% of its value but in the range from 0 to a 100%.

The result from the table 2 are drawn in figure 1. The horizontal axis represent ten steps, the step zero, in which the changing parameter has value of 30% (0% on the horizontal axis) described in the standard to step ten where the changed value has 70% (100% on the horizontal axis) of its interval described in the standard. The vertical axis represent corrosion rate calculated according the equation (1).
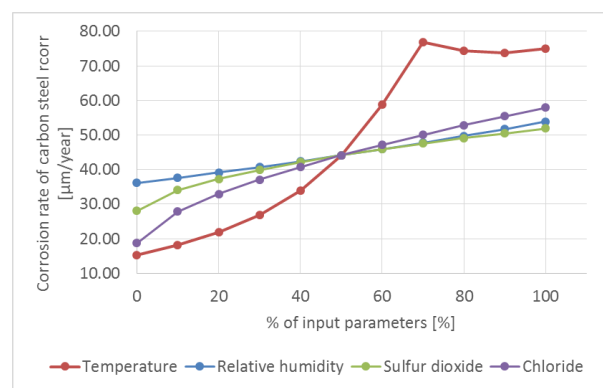

Figure 1. Input parameters are fixed at the mean values.

The sensitive analysis shows that the temperature the most affects the calculated corrosion rate of carbon steel. The corrosion rate is in the range from 15.27 to 76.77 µm/year (which represent increase by 61.50 µm/year). The chloride deposition rate is the second input parameter, which the most affect the calculated corrosion rate r_{corr}. It is in the range from 18.78 to 57.98 µm/year (increase by 39.20 µm/year).

In the real environment may occur various combination of values of the input parameters. It means that in the areas of high or low yearly concentration of temperature, relative humidity, sulphur dioxide or chloride deposition may occur the situation, where the fixed values are not represent by mean value but its high or low value. For this reason, these values are taken into account, in the second step of this research. These areas may be in the case of chloride deposition rate near the see or traffic infrastructure network where de-icing salt is applied [6-8]. The sulphur dioxide concentration is dominated in industrialized countries where is the higher level of atmospheric pollution [9]. The temperature and relative humidity may be dominated in the mountains or in the areas of different height above sea level.

Following figures show the situation, where all the parameters are fixed on the thirty (figure 2) or seventy percentages (figure 3) of its intervals according to standard and only one, calculated parameter, is changed. On these figures can be seen that the corrosion rate r_{corr} may be interfaced by changing of fixed input parameters. Figure 2 shows the situation when all fixed parameters are fixed on its thirty percentage and it is show that violet-chloride ions line is dominated and not red-temperature line as it was before. This leads to the conclusion that the calculated corrosion rate r_{corr} depends on the values of input fixed parameters (their mean, minimum, maximum and so on).

For this reason the graphs in figures 4-11 were made, where only one value was fixed on its 30 or 70 percentage.
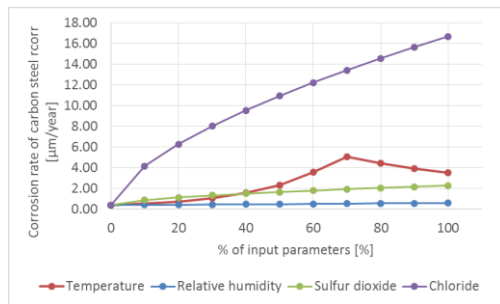
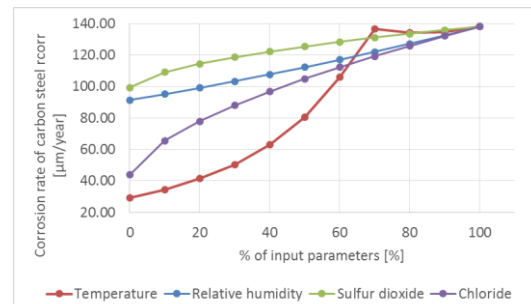**Figure 2.** Input parameters are fixed at 30% of its value.

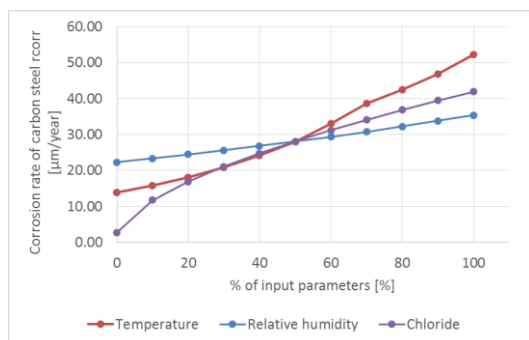**Figure 3.** Input parameters are fixed at 70% of its value.

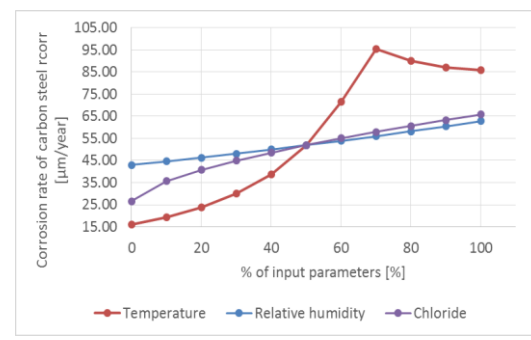**Figure 4.** SO₂ is fixed on its 30% value.

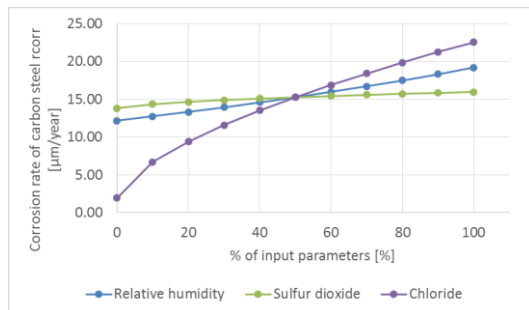**Figure 5.** SO₂ is fixed on its 70% value.

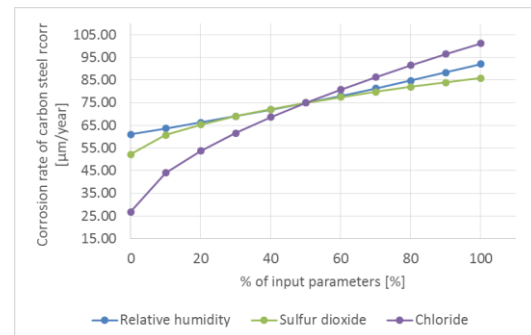**Figure 6.** Temperature is fixed on its 30% value.

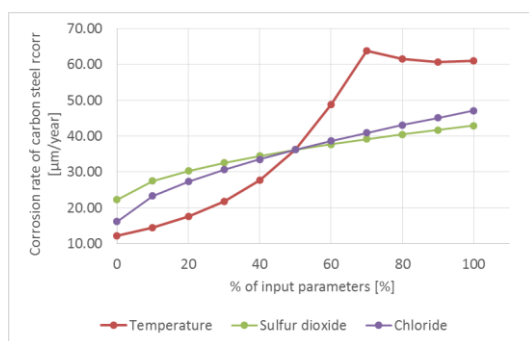**Figure 7.** Temperature is fixed on its 70% value.

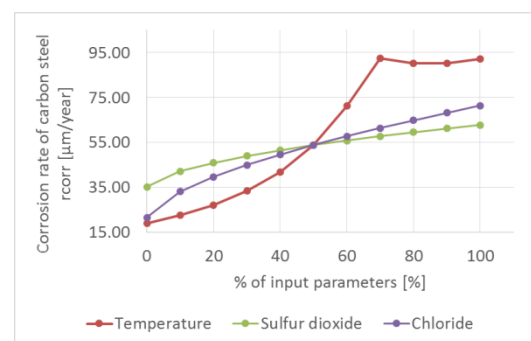**Figure 8.** Relative humidity is fixed on its 30% value.

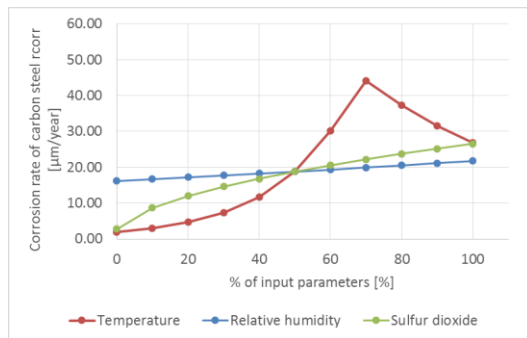**Figure 9.** Relative humidity is fixed on its 70% value.
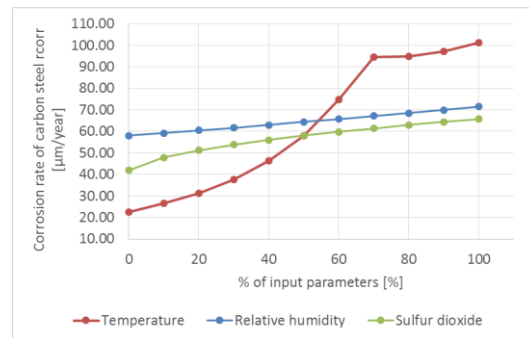
Figure 10. Chloride ions are fixed on its 30% value.

Figure 11. Chloride ions are fixed on its 70% value.

Figure 4 shows that the corrosion rate r_{corr} is in range from 2.74 µm/year to 41.94 µm/year (increases by 39.20 µm/year) for violet-chloride ions line. This corrosion rate (violet-chloride ions line) is calculated according to equation (1), when the input parameters like temperature and relative humidity are on their average values (T = 4.06 ˚C and Rh = 57,90 %), while the sulphur dioxide SO_2 value is on its 30% recommendation in the standard ($SO_2 = 1.14$ mg/($m^2 \cdot$ day)). The chloride deposition rate is changing parameter in calculation and is in range from 30 % to 70% recommendation in the standard ($Cl^- = 0.52 - 532.34$ mg/($m^2 \cdot$ day)). This extend (from 30% to 70%) is represented from zero to a hundred percentage, see horizontal axis of figure 4. Another two lines, in figure 4, were made in the same way, whereas the temperature (red-temperature line) or relative humidity (blue-relative humidity line) were changing parameters. Another graphs in figures 5-11 were made by the same procedure.

On these graphs, range of the corrosion rate r_{corr} was observed. In the case of violet-chloride ions line, it can be seen that the calculated corrosion rate r_{corr} is influenced by fixed SO_2 concentration on the 30 % of its value, figure 4 or by temperature concentration fixed on its 70 % of its value, figure 7. In these two cases, the calculated corrosion rate is in the range of 39.20 µm/year (in the case of 30 % of SO_2 concentration) and 74.42 µm/year (in the case of 70 % of temperature concentration). The results from figures 5-11 are summarized in the table below.

Table 3. Sensitive analysis of the dose-response function for the carbon steel.

	SO$_2$ - fixed on its		T - fixed on its		Rh - fixed on its		Cl$^-$ - fixed on its	
	30%	70%	30%	70%	30%	70%	30%	70%
	Range of the corrosion rate r_{corr} (µm/year)							
Sulphur dioxide line	-	-	2.15	33.69	20.64	27.53	23.83	23.83
Temperature line	38.41	79.32	-	-	51.72	73.27	42.03	78.65
Relative humidity line	13,05	19.93	7.01	31.01	-	-	5.53	13.48
Chloride ions line	39.20	39.20	20.64	74.42	30.91	49.71	-	-
Figure	4	5	6	7	8	9	10	11

3. Conclusion

The article was focused on the sensitive analysis of the dose-response function for carbon steel. The standard EN ISO 9223 [4] recommends the intervals for input parameters as sulphur dioxide, relative humidity, temperature and chloride ions. The range from 30 to 70 percentage of these recommended intervals were chosen for the analysis of the function. Generally, it is recommended as a fixed input parameter, for sensitive analysis, choose either the mean or the most frequent value. For this reason, when it is not known the most frequent values, the various combinations of fixed parameters were selected. It has to be mentioned, that the dose-response function was derived from the corrosion rate of the specimens under real atmospheric environment and it is the reason, why it is possible to make same particular conclusions on the base of the corrosion rate according this function.

The individual results show that the corrosion rate r_{corr} is mostly depending on the changing of the temperature and then on the changing concentration of the chloride ions. In the case, when all fixed input parameters are fixed in their thirty percentage, the change of chloride ions value the most attached the calculated corrosion rate. In the last step of this research only one parameter was fixed on its 30 or 70 percentage and the chloride ions curves were observed. The highest corrosion range, for the chloride ions line were either, when the temperature was on its 70% whilst another two fixed parameters were on their mean value (relative humidity and sulphur dioxide) or when the sulphur dioxide was fixed on its 30% (temperature and relative humidity was fixed in their mean value). This leads to the conclusion that the decreasing of SO_2 and increasing of temperature (such as in the case of global climate change) may causes the higher sensitivity of the corrosion rate r_{corr} equation on the chloride ions concentration.

Based on the dose-response function, the maps of corrosion rate can be created. For creation of these maps, the number and frequency of measurement stations are important. The temperature is measured in about 120 measurement stations in Slovakia by Slovak hydrometeorogical institute, which may be sufficient for creating these maps [5]. But the chloride deposition rate is not measured and so it is important to create the measurement stations mainly near the traffic infrastructure network, where the chloride ions are dominated due to de-icing salt.

Creation of the new corrosion stations with the specimens of non-protected (structural steel) and protected carbon steel by concrete (reinforced concrete) should by created in the areas where the temperature or chloride ions are dominated (near the traffic infrastructure network and/or in the area, where the temperature is higher like western part of Slovakia).

It may by mentioned that another point of the research should be the sensitive analysis in the interval of Slovakia's input parameters measured by Slovakia by Slovak hydrometeorogical institute.

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