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# Drugačna metoda določevanja koncentracij plinov zaprtih prostorov v odvisnosti od časa

## Alternative Method for Determine Concentration of Gases in Enclosed Structures as a Function of Time

**Jakob Likar - Jure Čadež**

*V prispevku je predlagan drugačen postopek projektiranja prezračevalnih sistemov v zaprtih in deloma zaprtih podzemnih prostorih, kjer se pokaže potreba po bolj podrobnih analizah. Podane so teoretične osnove in področja uporabe. Za prikaz prednosti takšnega postopka je opravljen izračun gibanja onesnaženega zraka v zaprtem prostoru v odvisnosti od časa.*

**(Ključne besede: prostori zaprti, zrak onesnažen, prezračevanje, koncentracije plinov)**

*This paper proposes an alternative approach to the ventilation design of enclosed and half enclosed underground structures, where more detailed analysis is required. Theoretical basics are represented and the area of application is determined. To show the advantage of such approach a calculation of movement of exhausted air through enclosed structure as function of time has been executed.*

**(Keywords: enclosed structures, polluted air, ventilation, gas concentration)**

### 0 UVOD

Pri gradnji in obratovanju podzemnih prostorov, npr. predorov, podzemnih garaž, rudnikov itn., pomeni projektiranje prezračevanja podzemnih prostorov velik izziv. Prezračevalni sistemi dovajajo svež zrak in odvajajo onesnaženega. Pri izkopu predorov in pridobivanju rude v rudnikih je zrak onesnažen iz dveh virov. Prvi vir sta ogljikov dioksid in monoksid, ki nastajata pri delovanju motorjev z notranjim zgorevanjem. Hribina ali zemljina, v kateri se izvaja izkop, vsebuje pline, kakršna sta metan ali ogljikov dioksid. Mešanica metana in zraka je pri koncentracijah med 4 in 15 % metana eksplozivna, zato mora biti ta pravočasno odveden s področja odkopavanja.

V podzemnih garažah je zrak onesnažen samo iz prvega vira.

Prezračevalni sistem ustvarja tok zraka, ki odvaja onesnažen zrak s področja izkopavanja, ali v drugem primeru, s področja prometa v podzemnih garažah. V kotih prostorov oziroma mestih, kjer

### 0 INTRODUCTION

In the construction of enclosed and half-enclosed structures, such as tunnels, underground car-parks, mines etc., the design of the ventilation system presents a considerable challenge. In this kind of structure mechanical ventilation systems are installed to supply fresh air and to remove the polluted air. During the excavation of tunnels and the extraction of ore from mines the air is polluted for two reasons. The first is the carbon monoxide and dioxide that comes from the exhausts of machines or vehicles with internal combustion engines. The second is that the rock or soil often contain gases such as methane and carbon dioxide. When mixed with air in the concentration range of 4 to 15 % methane is explosive and must be removed from the area of excavation.

In underground car parks, of course, the air is polluted only for the first reason.

The ventilation system produces an airflow, which removes the polluted air from the domain of excavation or, in the other case, from the domain of the traffic. In the corners of underground structures prezračevanje ni učinkovito, lahko nastane območje velike koncentracije onesnaženega zraka; še posebej je nevaren metan, ki je, pomešan z zrakom, eksploziven.

Predpisi na področju prezračevanja upoštevajo največjo in povprečne vrednosti koncentracije plinov v zaprtih in polzaprtih prostorih, na podlagi katerih so projektirani prezračevalni sistemi. Prav tako je navadno predpisana najmanjša potrebna količina zraka.

V prej navedenih primerih projektiranje ventilacije po teh kriterijih ne obvaruje delavcev in uporabnikov podzemnih garaž pred škodljivimi vplivi. V teh primerih je treba izvesti dodatne analize. V tem prispevku predlagamo alternativno metodo projektiranja prezračevanja, ki omogoča bolj podrobno analizo dogajanja in omogoča spremljanje koncentracij onesnaževalnikov v odvisnosti od časa.

or places where ventilation is ineffective, a high concentration of polluted air can occur. This is especially dangerous in the case of methane, which is explosive when mixed with air.

In general, a ventilation system is designed with the criteria of maximum and average concentrations of gases in enclosed and half enclosed underground structures taken into consideration. The minimum volume of fresh air is determined as well.

In the special cases mentioned above, basing the size of the ventilation system on those criteria does not prevent workers or passengers from being exposed to danger: the problem must be explored in greater detail. In this article we propose an alternative method for determining the dimensions of a ventilation system, which allows a detailed analysis of the problem and shows the change in the concentration of pollutants as a function of time.

## 1 TEORETIČNE OSNOVE

Koncentracija plinov v nekem prostoru je odvisna od naslednjih parametrov:

- lege vira plina,
- izdatnosti vira plina,
- lege vira svežega zraka,
- količine svežega zraka,
- velikosti prostora.

Če razdelimo prostor na posamezne dele ali cone (nadzorne prostornine, sl. 1), lahko za vsako cono zapišemo masno bilanco, kakor je navedeno v enačbi 1 ([1] in [5]):

## 1 THEORETICAL CONSIDERATION

Generally, the concentration of gases depends on the following parameters:

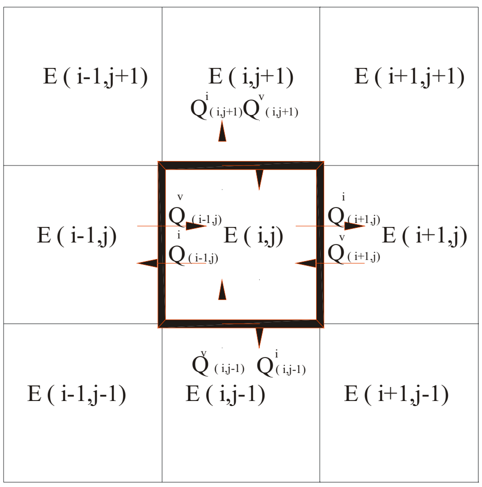
- position of the gas source
- emission rate of gas source
- position of the fresh-air intake
- volume of fresh air
- volume of the structure

If we divide the underground space into a number of zones (control volumes, see Figure 1), the mass balance for each zone can be represented as follows ([1] and [5]):

$$\rho . V_{ij} . \frac{dC_{ij}(t)}{dt} = C_{ij}^{v}(t) - C_{ij}^{i}(t) + S(t)_{ij} \quad (1),$$

$V_{ij}$ - prostrnina cone, $C_{ij}$ - koncentracija plina v posamezni coni, $C_{ij}^{v}$ - dotok zraka z določeno koncentracijo plina iz sosednjih con, $C_{ij}^{i}$ - odtok zraka z določeno koncentracijo plina v sosednje cone, $S(t)_{ij}$

$V_{ij}$ - volume of zone, $C_{ij}$ - concentration of gas in current zone, $C_{ij}^{v}$ - incoming air with concentration of gas from connected zones, $C_{ij}^{i}$ - outgoing air to the connected zones, $S(t)_{ij}$ - emission rate of gas, $Q_{ij}^{v}$ - incoming




Sl. 1. *Masna bilanca za cono i, j*

Fig. 1. *Mass balance for zone i, j*

- emisija plina, $Q_{ij}^{v}$ - dotok zraka iz sosednjih con, $Q_{ij}^{i}$ - odtok zraka v sosednje cone, i,j - indeksi.

Enačbe koncentracij plinov, ki vstopajo ali izstopajo iz posamezne cone, so:

volume of air from connected zones, $Q_{ij}^{i}$ - outgoing volume of air to the connected zones, i,j - index.

The expression for the gas concentrations that enters or leaves a zone:

$$C_{ij}^{v}(t)=Q_{i-1,j}^{v}.C_{i-1,j}^{v}(t)+Q_{i+1,j}^{v}.C_{i+1,j}^{v}(t)+Q_{i,j-1}^{v}.C_{i,j-1}^{v}(t)+Q_{i,j+1}^{v}.C_{i,j+1}^{v}(t) \quad (2)$$

$$C_{ij}^{i}(t)=Q_{i,j}^{i}.C_{i-1,j}^{i}(t)+Q_{i,j}^{i}.C_{i+1,j}^{i}(t)+Q_{i,j}^{i}.C_{i,j-1}^{i}(t)+Q_{i,j}^{i}.C_{i,j+1}^{i}(t) \quad (3).$$

Sistem navadnih diferencialnih enačb prvega reda je tako določen. Enačbe je mogoče rešiti ob definiciji ustreznih robnih pogojev in poznavanju pretoka zraka prek robov posamezne cone.

Robni pogoji za posamezen element so koncentracije plina v času nič (začetna koncentracija).

Gibanje zraka skozi zaprt prostor je mogoče določiti s programi, ki se uporabljajo za analize s področja dinamike tekočin in slonijo na numeričnih metodah. V tem primeru je bil uporabljen program ANSYS (FLOTRAN), izračun pa je bil napisan na Fakulteti za strojništvo v Ljubljani. Rezultat analize je polje hitrosti zraka, ki jih program izračuna za ogljišča vsakega elementa posebej. Vektorji hitrosti so preneseni v program MATHEMATICA, v. 2.2, kjer je bila izračunana povprečna hitrost zraka prek robov vsakega elementa. Pretok zraka prek robov elementov za vsak element posebej je mogoče določiti s poznavanjem dolžine stranice vsakega elementa in povprečne hitrosti zraka prek nje.

Lego vira svežega zraka je treba določiti v numerični analizi, pri izračunu koncentracij pa je treba določiti še lego vira plina in emisijo plina v posamezni coni.

Sistem diferencialnih enačb ni analitično rešljiv, ampak samo numerično. Rezultat izračuna je koncentracija plina v vsaki coni v odvisnosti od časa. Za reševanje velikih sistemov diferencialnih enačb potrebujemo posebne programe in zmogljive računalnike. Za zdaj je za razumljivo manjše število con mogoče izračunati koncentracijo plina za nekaj minut. Vsi izračuni so bili opravljeni s programom MATHEMATICA, v. 2.2.

So, a set of ordinary differential equations is defined. These equations can be solved after defining the boundary conditions and the airflow rate for each zone.

The boundary condition for each element is simply the concentration of gas in each zone at time zero (initial concentration).

A numerical analysis of airflow movement through enclosed underground structure was made calculated with the technique of computational fluid dynamics or CDF (ANSYS, FLOTRAN). The simulation was made at the Faculty of Mechanical Engineering in Ljubljana. The result of the analysis is a field of air velocity, which can be calculated for the corners of each element. The velocity vectors for each corner were entered into the MATHEMATICA v. 2.2 program, where an average velocity of airflow through the boundary lines of each zone was calculated. A volume of airflow for each zone can now be determined by knowing the average velocity and the length of the boundary line.

The position and the volume of the fresh-air source is determined by a numerical analysis of the air flow, while the position of the gas source and the emission rate can be defined for each zone.

The set of differential equations can only be solved numerically and the result is the concentration of gas in each zone as a function of time. However, solving a large set of equations requires special program equipment and for a long-term analysis a lot of time is needed. At present for a reasonable number of zones, the concentration of gas in each element can be calculated in a few minutes. All the calculations were executed with the MATHEMATICA, v. 2.2 program.

## 2 PRIMER IZRAČUNA

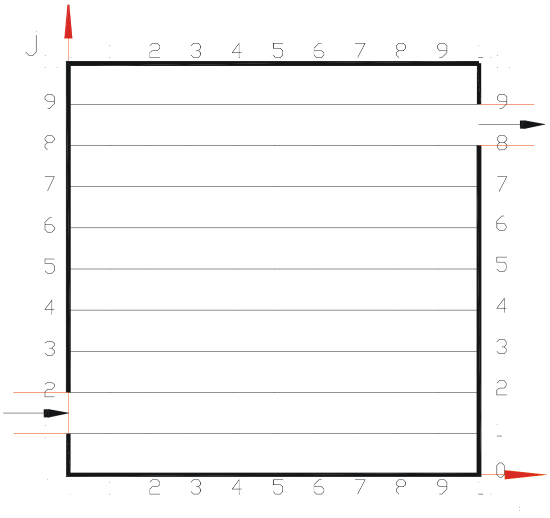
Da bi lahko predstavili prednosti takšnega postopka, je bil izveden hipotetični izračun,

Prostor smo razdelili na sto con (elementov) z enako površino, kakor je prikazano na sliki 2. Svež zrak prihaja v prostor v spodnjem delu prostora, onesnažen zrak pa zapušča prostor v desnem zgornjem delu prostora. Hitrost zraka na vstopu in izstopu iz prostora je enaka in znaša 1 m/s. Slika 3 prikazuje polje hitrosti kot rezultat izračuna z računalniško dinamiko tekočin. Predpostavili smo, da je začetna koncentracija plina v vseh conah enaka nič (robni pogoji). Vir

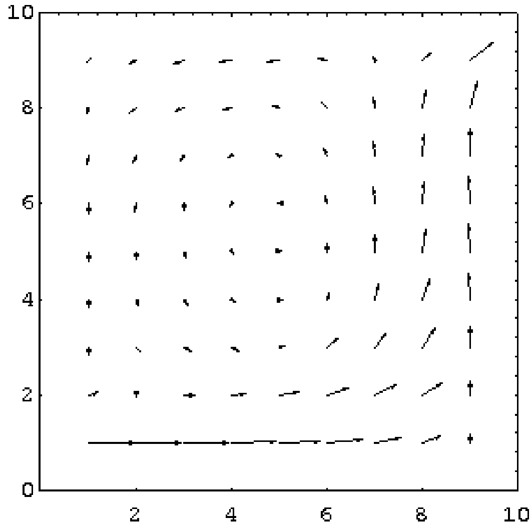
## 2 A CASE STUDY

As an example a hypothetical calculation has been made to show the advantage of such an approach to the problem.

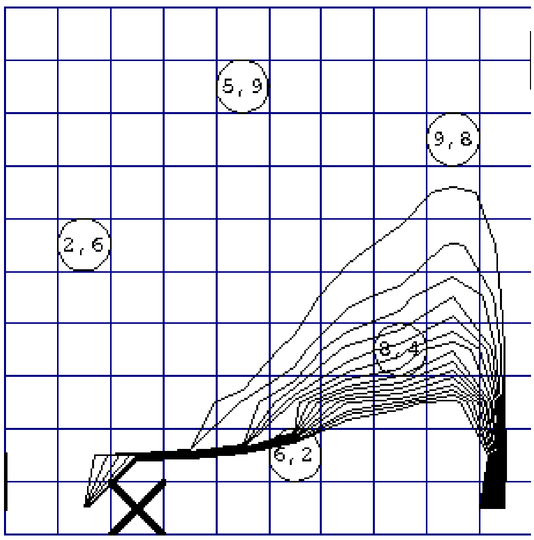
The space of the structure is divided into a hundred zones with equal shape (1 m$^2$), which is shown in Figure 2. Fresh air enters at the bottom left corner, and the exhausted air leaves the structure at the top right corner. The velocity of the incoming fresh air and outgoing exhausted air is 1 m/s. Figure 3 shows the air velocity field for such a model, calculated with CDF. The initial concentration of gas is assumed to be zero. The source of the gas is placed



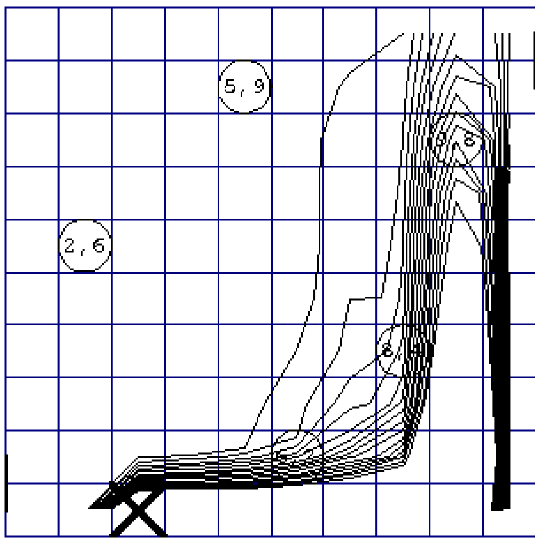

Sl. 2. *Prostor, razdeljen v 100 con z označenimi legami dotoka svežega zraka in iztoka onesnaženega zraka*
Fig. 2. *Shape of the space, divided into a hundred of zones, with position of incoming fresh air and outgoing exhaust*




Sl. 3. *Polje hitrosti*
Fig. 3. *Velocity field*




Sl. 4. *Koncentracija plina po desetih sekundah*
Fig. 4. *Concentration of gas after 10 seconds*




Sl. 5. *Koncentracija plina po tridesetih sekundah*
Fig. 5. *Concentration of gas after 30 seconds*

plina oz. onesnaženja se nahaja v spodnjem levem prostoru in je označen s križem, emisija pa znaša 0,4 l/s. Koncentracija plina v odvisnosti od časa je izračunana v conah, ki so označene s krogi na slikah 4, 5 in 6.

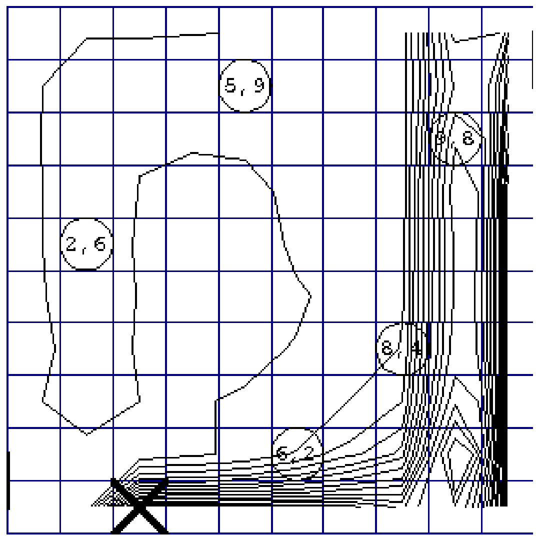
Slike 4, 5 in 6 prikazujejo gibanje onesnaženega zraka v času 10, 30 in 180 sekund po začetku emisije plina.

Koncentracije plina v conah v odvisnosti od časa so prikazane na slikah od 7 do 11 in predstavljajo povečanje koncentracije plina za različne dele prostora v odvisnosti od časa. Koncentracije so prikazane v milijoninkah (ppm = $10^{-6}$).

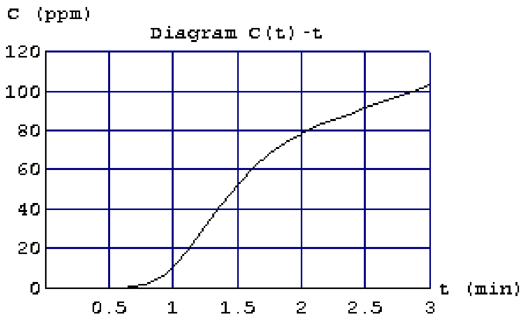
on the bottom left of the space, the emission rate is 0.4 l/s. A cross indicates the source of the pollution. The concentration is measured in zones marked with circles in Figures 4,5 and 6. At this point the calculation can be executed.

Figures 4,5 and 6 show the movement of the exhausted air through the space for 10, 30, and 180 seconds after the gas source becomes active.

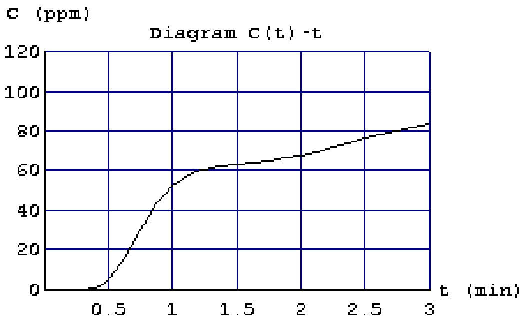
The concentration in zones as a function of time is presented in Figures 7 to 11, which show an increasing gas concentration for different parts of the space as a function of time. The concentration is expressed in parts per million (ppm = $10^{-6}$).



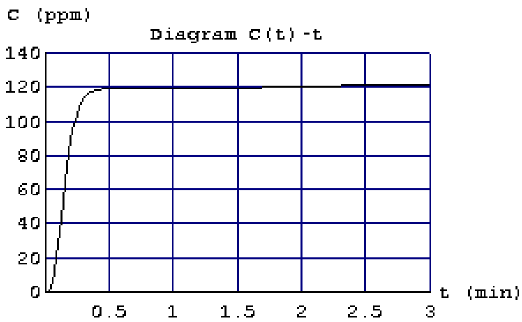

Sl. 6. *Koncentracija plina po sto osemdesetih sekundah*
Fig. 6. *Concentration of gas after 180 seconds*



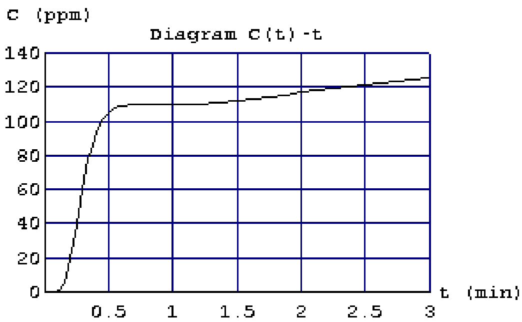

Sl. 7. *Koncentracija plina v coni (2,6) v odvisnosti od časa*
Fig. 7. *Concentration of gas in zone (2,6) as a function of time*




Sl. 8. *Koncentracija plina v coni (5,9) v odvisnosti od časa*
Fig. 8. *Concentration of gas in zone (5,9) as a function of time*




Sl. 9. *Koncentracija plina v coni (6,2) v odvisnosti od časa*
Fig. 9. *Concentration of gas in zone (6,2) as a function of time*



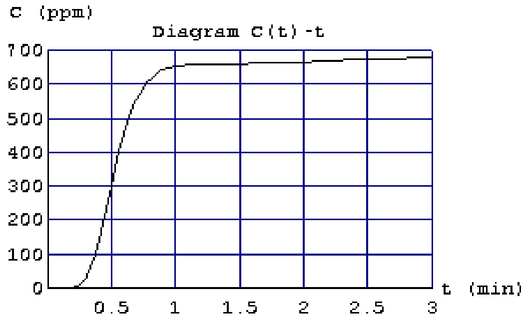

Sl. 10. *Koncentracija plina v coni (8,4) v odvisnosti od časa*
Fig. 10. *Concentration of gas in zone (8,4) as a function of time*

Koncentracije v conah desno od vira plina in vira svežega zraka dosežejo velike vrednosti kmalu po začetku izračuna. V drugih conah, razen cone (9,8), se koncentracija zvečuje počasneje.

Cona (9,8) leži na "križišču", kjer je dotok onesnaženega zraka v to cono večji od iztoka.

The concentration in the zones close to the source of the gas and the intake of fresh air indicates the high values of the concentration very soon after the calculation is started. In other zones, except zone (9,8) concentrations increased slowly.

Zone (9,8) lies at a "crossing" where the rate of the incoming polluted air is higher than the outgoing




Sl. 11. *Koncentracija plina v coni (9,8) v odvisnosti od časa*
Fig. 11. *Concentration of gas in zone (9,8) as a function of time*

Koncentracija v tem elementu je šest- ali sedemkrat večja kakor v drugih conah.

Raven koncentracije plina oziroma onesnaženja v posameznih delih prostora je zelo odvisna od lege dovoda svežega zraka in lege vira onesnaženja. Drugačna ureditev, kakor je prikazana v obravnavanem primeru, bi bistveno spremenila gibanje zraka skozi prostor, kar lahko vpliva na učinkovitost prezračevanja. Lega vira onesnaženja in predel, kjer prezračevanje ni učinkovito, bi povzročila zelo velike lokalne koncentracije onesnaženja.

from the present element. The concentration level in this zone is 6 or 7 times higher than in other zones.

It is clear that the increase in the concentration depends strongly on the position of the fresh-air intake and on the position of the gas source. A different location of the incoming fresh air and outgoing polluted air would change the movement of air through space, which can decrease or increase the efficiency of the ventilation system. The position of the source of the pollution in part of the space where the ventilation is not effective would lead to very high local concentrations of polluted air or gas.

## 3 SKLEP

Tak postopek je mogoče uporabiti v posebnih primerih, pri katerih je potrebno boljše poznavanje gibanja koncentracij v nekem prostoru. Mogoče ga je uporabiti pri gradnji prezračevanja predorov v fazi gradnje, ko je treba določiti mesta, kjer bi lahko nastajale velike koncentracije metana ali drugih plinov, še posebej pa za overitev učinkovitosti sedanjega prezračevalnega sistema. Poleg tega je tak postopek mogoče uporabiti tudi pri dimenzioniranju in preverjanju učinkovitosti prezračevalnega sistema v zaprtih prostorih, kjer obstajajo viri onesnaženja.

Koncentracije v posameznih conah je mogoče izračunati v odvisnosti od časa in tako določiti čas, v katerem bi v posameznih delih prostora prišlo do kritičnih koncentracij oziroma dele prostora, kjer bi bilo treba vgraditi zaznavala.

## 3 CONCLUSIONS

This approach can be used in special cases where more accurate results for the concentration of gases are required. It could be used in tunnels during the building phase to determine zones with high concentrations of methane and other gases, and especially for verifying the effectiveness of the existing ventilation system. In addition, this approach can also be used during dimensioning and verification of a ventilation system for enclosed structures where the source of the pollution exists.

The concentrations can be calculated as a function of real time, so the time during which the concentration in the examined zone becomes critical can be determined, or alternatively, critical zones in which sensors should be installed can be specified.

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