A SOFTWARE FOR ASSESSING PERSONAL EXPOSURE IN URBAN AREAS BASED ON COMBINED DOSE AND EXPOSURE INDICATORS

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EXTENDED ABSTRACT

This paper describes the Combined Environmental Stressors’ Exposure (CENSE) tool and its application in the metropolitan Thessaloniki center. CENSE is a software for assessing personal exposure in urban areas based on combined dose and exposure indicators theory. Characterization of personal exposure is of vital importance in urban areas, since citizens spend a substantial portion of their time in spaces where exposures to pollutants are often highly elevated. Furthermore, an urban space or microenvironment needs to be characterized according to its environmental quality, especially if it is densely populated or usually crowded. This space may be a closed environment (e.g. the interior of a car) as much as an open-air one (such as the saddle of a motor- or bi-cycle, or even the pavement used by pedestrians). As individuals are exposed to mixtures of environmental health stressors that comprise several environmental exposures simultaneously there is also a need to holistically address combined exposures. Environmental exposures induce direct and indirect health responses to humans. Their effects may vary during lifetime and possibly depend on the presence of other stressors in a combined and/or a synergetic manner. Provided that environmental stressors are taken in combination, they possibly represent a more serious environmental hazard to public health. Environmental quality varies in time and space as the result of the combined action of different pollutants and ultimately impacts on humans. Consequently, there is a need to address co-exposure in a holistic way. Rather than viewing chemical and physical health stressors separately for decision making and environmental sustainability considerations, the possibility of an easy-to-comprehend co-exposure assessment is herein considered. The CENSE tool is developed for this reason, considering citizens’ activities in urban areas. CENSE has been fully developed in the programming environment of Delphi. The graphical users interface facilitates its tractable application. Studying of different scenarios is easy since the execution time required is negligible. The tool incorporates the co-exposure indicators’ theory and takes into account the potential relative intake of each chemical stressor by considering the physical activities of each citizen. The capabilities of the CENSE tool are demonstrated through its application for the case of Thessaloniki, Greece. The test case incorporates the local features into a well identified user/decision maker interface that takes into account the specific characteristics of the area considered.

Keywords: CENSE, environmental health stressors, exposure assessment, air quality, noise pollution, combined dose and exposure indicators.

1. INTRODUCTION

Over the past decades, there has been great concern regarding air quality in urban centers. As a result of urbanization, such areas often present high levels of environmental health stressors, due to the combination of large number of citizens and their corresponding activities. It is generally accepted that exposure to such environmental
stressors, even though it mainly characterizes densely populated urban areas such as metropolitan centers and urban core microenvironments (Vardoulakis et al., 2011), may pose serious implications for health and environmental management (Sokhi et al., 2006). It is commonly accepted between health experts that, even in current ambient urban levels, chemical air stressors aggravate morbidity and may lead to premature mortality (Pope et al., 2011). Furthermore, excessive exposure to physical stressors such as noise or radiation, is associated with annoyance and reduced quality of life (Murphy et al., 2009). There is also concern about the possible health impacts related to the modification of environmental variables due to the climate change (e.g. extreme cold or heat stress may have acute and medium term effects) (D'Ippoliti et al., 2010), and aeroallergens such as pollens, especially those with high allergic potential for children (Reid and Gamble, 2009). Finally, it is highly probable that there is a large number of health stressors yet to be discovered, since the current state of knowledge has still gaps and numerous uncertainties (Vlachokostas et al., 2012b).

On the basis of the aforementioned, an urban space or microenvironment needs to be characterized according to its air quality. Exposure to environmental health stressors is meaningful where there is high density of receptors. Thus, the prior characterization is even more crucial in densely populated or usually crowded spaces. And that is because on the one hand citizens have to spend a substantial amount of time in spaces where exposure to health stressors is often highly elevated, while on the other hand, their corresponding activities are likely to induce emission of potentially hazardous environmental health stressors. The space of interest may either be a closed environment with well-defined boundaries (e.g. the interior of a car), or an open-air one such the saddle of a bicycle or the pavement that pedestrians use to walk. Individuals are often exposed to a mixture of pollutants, rather than being exposed to a pollutant in particular. As a result, exposure to environmental health stressors in urban areas, should be assessed in a holistic and integrated way (Vlachokostas et al., 2012a). Exposure to environmental health stressors is known to induce direct and indirect responses to humans. Furthermore, the effects may vary significantly from individual to individual and are highly dependent upon the presence of other stressors, since there are complex synergistic mechanisms between different pollutants. Provided that environmental stressors are regarded in combination, and given the fact that environmental quality is time and space dependent (Carnevale et al., 2012), characterization of urban spaces relevant to decision making should include a vast amount of information about each particular stressor.

This paper presents the Combined ENvironmental Stressors’ Exposure (CENSE) tool. CENSE is a tool developed to assess combined exposure to environmental pressures in urban areas in a holistic and easy to comprehend manner. On top of being able to take multiple stressors into account, it is also designed to account for the citizens’ activities. Whether those activities include commuters driving or riding means of transport in traffic (e.g. driving a car or riding a bicycle or motorcycle), walking (as well as standing or running) in busy and congested streets, or even working or living in busy and trafficked roads, the performed activity is of great importance in the effort to assess combined exposure to environmental health stressors in urban areas.

2. **THE SOFTWARE**

2.1. **Theoretical background**

CENSE enables the user to assess combined exposure in urban areas. In order to do so, it calculates the levels of combined exposure making use of two cumulative exposure indicators i.e. the Combined Exposure Factor (CEF) and the Combined Dose and
Exposure Factor (CDEF) (Vlachokostas et al., 2012a). CEF is algebraically incorporated into the algorithmic model as:

\[
CEF(T) = \sum_{i=1}^{P} w_i \cdot \frac{E_i(i) - E_t(i)}{E_t(i)}
\]

where:
- \(CEF(T)\): Combined Exposure Factor, \(-1 \leq CEF(T) \leq +\infty\).
- \(P\): Number of environmental health stressors considered in the analysis, \(1 \leq P \leq \infty\).
- \(w_i\): Weighting factor for environmental health stressor \(i\).
- \(E_i(i)\): Limit value of exposure to environmental health stressor \(i\).
- \(E_t(i)\): Average exposure to environmental health stressor \(i\).

CEF captures co-exposure to several environmental health stressors with the weighted average of sub-indices that express the relative weight of the exposure levels compared to the limit value of the exposure. The numerator represent the margin of exposure (MOE), which is widely used in exposure and risk assessment of environmental chemicals (Lewalle, 1999). That limit value can be a legislative environmental quality standard or any other exposure level that can be perceived as a threshold. However, for the case of carcinogenic environmental stressors such as benzene, zero may be used as a threshold. On top of the CEF concept, the combined dose and exposure factor (CDEF) concept is also proposed in an attempt to take into account the potential relative uptake of chemical health stressors due to the respiratory rates by considering individuals' activities. CDEF is algebraically incorporated into the algorithmic model as:

\[
CDEF(T) = \sum_{j=1}^{J} w_j \cdot \frac{D_j(j) - D_t(j)}{D_t(j)} + \sum_{r=1}^{R} w_r \cdot \frac{E_t(r) - E_t(r)}{E_t(r)}
\]

where:
- \(CDEF(T)\): Combined Dose and Exposure Factor, \(-1 \leq CDEF(T) \leq +\infty\).
- \(J\): Number of chemical health stressors with estimated intake considered in the analysis, \(1 \leq J \leq \infty\).
- \(w_j\): Weighting factor for chemical health stressor \(j\).
- \(D_j(j)\): Upper dose equivalent to \(E_t(j)\) for chemical stressor \(j\).
- \(D_t(j)\): Average dose that can be attributed to \(E_t(j)\), based on the estimated relative uptake of pollutant \(j\).
- \(Q_{air}\): Typical minute air volume (l/min), which is the product of the average respiratory rate (breaths/min) and the volume per breath.
- \(Q_{air, min}\): Minimum typical minute air volume.
- \(R\): Number of physical health stressors considered in the analysis, \(1 \leq R \leq \infty\).
- \(w_r\): Weighting factor for physical stressor \(r\).
- \(E_t(r)\): Limit value of exposure to physical stressor \(r\).
- \(E_t(r)\): Average exposure to physical stressor \(r\).

In a sense, CDEF provides a “correction” to the CEF indicator by offering a characterization in terms of the potential dose of the recipient rather than just the exposure. However, when the dose approach cannot be used, e.g. in case of physical stressors such as noise or radiation, the CDEF formulation keeps the rationale mentioned in the analysis of the CEF indicator. The scale of how CEF/CDEF values proposed by the aforementioned methodological scheme and adopted by the CENSE tool, relate to actual exposure levels and characterizations is indicated in figure 1.
More information regarding the co-exposure indicators concept can be found in the detailed work of Vlachokostas et al (2012a).

2.2. Technical background

The CENSE tool is an application entirely designed in the object oriented programming (OOP) environment of Delphi 10. Delphi, as part of the Embarcadero rapid application development (RAD) studio features a number of advantages, enabling the developer to create cross-platform applications that feature appealing graphical user interface (GUI) and powerful capabilities.

CENSE incorporates the theory analyzed above, into a distinct, easy-to-use framework, without compromising the capabilities and the flexibility of the CEF/CDEF indicator approach. The main stages in the assessment are presented in figure 2. After the introductory form where general information about CENSE may be obtained, the user can proceed to the main form. The main form features a tabbed design, so that the user is discretely guided through the process. Initially, the problem must be fully defined. In order for the problem to be defined, the user has to provide the input data regarding the location of the urban space or microenvironment, as well as the stressors and activities that will be taken into consideration. This should be done through the “Location”, “Stressors” and “Activities” tabs respectively. The location of interest is selected with the featured Google Maps API while for each stressor selected, the user has to provide the corresponding weighting factor, threshold and measurement. CENSE features a set of tools making the process of inserting the stressor data easier such as the option to load the measurement data from a file, and the option to apply various filters. For each activity taken into consideration the typical minute air volume must also be provided, in addition to the minimum minute air volume. The user has the option to change the default values recommended by the analytical work of Adams (1993), McNabola et al. (2007) and Vlachokostas et al. (2012a). After providing all the required data, the user may proceed in calculating the CEF and CDEF per activity indicators in the “Results” tab. Finally, a report containing the main input data, the results and a cumulative representative graph can be obtained through the “Report” tab.

The software features a user friendly design, making it possible for inexperienced users to use the software in order to conduct an assessment. There is a great deal of supportive features, which combined with the negligible time required for calculation, make CENSE a really useful tool for assessing combined exposure to health stressors in urban areas. More information on CENSE’s technical background and operation instructions can be found in the operation manual (aix.meng.auth.gr/~vlahoco/cense.exe).
CASE STUDY

3.1. Location

As mentioned above, the urban space and/or microenvironment for which the assessment will be conducted is of great significance, because of the fact that it combines some specific characteristics. Exposure to stressors is meaningful in spaces that combine high stressor concentrations and high receptor density and activities. Thus, for the particular case study, Thessaloniki’s city center was chosen.

Thessaloniki is the second largest Greek city, and is located in northern Greece. It is one of the largest and most populated cities in the Balkan region and a major economic, industrial, commercial and political center of the southern Europe. Due to its important geopolitical position, it is also a major transportation hub for the rest of the south-eastern Europe. Furthermore, the city center is pretty dense, featuring large numbers of citizens performing a wide variety of activities. In addition to the above, there is also a large number of vehicles commuting through the area, thus making this particular urban space ideal for air quality assessment.
3.2. Stressors

The stressors estimated in the analysis is of great importance, due to the fact that improper selection may produce misleading results. For this case study, fixed-site measurements for PM$_{10}$, NO$_2$ and O$_3$ conducted in the city center by the Air Pollution Monitoring Network of Central Macedonia Region are used. In addition to the above data, portable measurement data is also used for CO, VOCs, benzene and noise levels. (Vlachokostas et al., 2012a). The data covers a period from March 2010 until February 2011 for the morning and evening rush hours (09:00-11:00 and 19:00-21:00 respectively). The mean concentration for each stressor is shown in table 1.

The weighting factors provide means of giving relative importance to each stressor, considering the local characteristics. An experts’ group was set up in order to reliably decide upon the weighting factors for this case study. The decision was made on the basis of each stressor’s significance considering the association with specific health endpoints, perceived reliability of the available epidemiological associations and finally, the perceived status of each health stressor in the area compared to environmental standards. The weighting factors are shown in table 1. The upper threshold for each stressor, is also shown in table 1. For most of the stressors the air quality standards or guidelines were used, with the exception of benzene. For benzene, the zero threshold is proposed, on the basis of its high carcinogenic potential.

<table>
<thead>
<tr>
<th>Stressor</th>
<th>Relative Importance</th>
<th>Upper Threshold</th>
<th>Concentration 09:00-11:00</th>
<th>Concentration 19:00-21:00</th>
<th>Concentration Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>0.059</td>
<td>8.70 ppm</td>
<td>0.67</td>
<td>0.73</td>
<td>0.69</td>
</tr>
<tr>
<td>NO$_2$</td>
<td>0.085</td>
<td>200 μg/m$^3$</td>
<td>27.11</td>
<td>27.87</td>
<td>27.49</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>0.299</td>
<td>90 μg/m$^3$</td>
<td>51.03</td>
<td>48.94</td>
<td>49.98</td>
</tr>
<tr>
<td>O$_3$</td>
<td>0.108</td>
<td>120 μg/m$^3$</td>
<td>37.16</td>
<td>55.26</td>
<td>46.26</td>
</tr>
<tr>
<td>Benzene</td>
<td>0.246</td>
<td>0 ppb</td>
<td>0.68</td>
<td>0.72</td>
<td>0.69</td>
</tr>
<tr>
<td>VOCs</td>
<td>0.111</td>
<td>37.5 ppb</td>
<td>44.67</td>
<td>57.26</td>
<td>48.78</td>
</tr>
<tr>
<td>Noise</td>
<td>0.092</td>
<td>67 dB</td>
<td>66.83</td>
<td>64.32</td>
<td>65.57</td>
</tr>
</tbody>
</table>
3.3. Activities

All the activities with the exception of those involving cars or motorcycles were taken into account for the case study with their default minute air volumes. The reason for that exception is lack of representativity between the fixed-site measurements and the actual concentration in the traffic plume.

4. RESULTS

The results of the case study which are synoptically presented in figures 4 and 5, reveal a specific and relatively obvious pattern. While the CEF values for all the examined scenarios correspond to “Good” or “Very Good” levels of exposure, that’s not the case when the CDEF values are taken into account. CDEF values for mild physical activities also correspond to relatively good levels of exposure while CDEF values for intense physical activities correspond to worse levels, ranging from “Poor” to “Hazardous”. By a glance at the results the need to “correct” the CEF indicator with the CDEF is made obvious.

![Figure 4. CENSE’s cumulative report for the morning period](image)

![Figure 5. CENSE’s cumulative report for the evening period](image)
5. CONCLUSIONS

CENSE is the first software attempt to address combined exposure to health stressors in urban areas. It is capable of taking multiple chemical and physical stressors into account, minimizing calculation time and offering relatively easy to use functionality, while maintaining the underlying theory’s flexibility. Thus, using CENSE does not require much familiarity or advanced scientific knowledge, while it is fairly simple to apply CENSE for virtually any urban space, providing there is sufficient and reliable data. CENSE also provides tools for making data exchange easier among CENSE users.

However, CENSE is an application and it does not substitute the researcher. The results provided, are as accurate as the import data. Furthermore, it is not an epidemiology software and it would be wrong to view it like one. Thus, the use of CENSE highlights the need for extended study in order to fill the knowledge gap regarding various stressor synergies, as well as the need for portable measurement campaigns since it’s made fairly obvious that there are severe representativity issues with fixed-site measurements. Nevertheless, CENSE can be a useful tool in urban planning and sustainability considerations.

REFERENCES