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Modelling of Indoor Air Quality of Greek Apartments Using CONTAM(W) Software

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Abstract

Indoor air quality (IAQ) is an active field of research due to the health impacts that the air pollutants impose to humans. To investigate the situation for Greece, this study modelled with CONTAM(W) the distribution of concentrations of certain air pollutants that are present in Greek dwellings. For the simulations, typical Greek dwellings were described in CONTAM(W) and certain air pollutants were added to modelling scenarios. The investigated pollutants were the carbon monoxide (CO), the nitrogen dioxide (NO_2), the particulate matter ($PM_{2.5}$), radon (^{222}Rn) and formaldehyde (CH_2O). To specialize for Greece, several parameters were properly adjusted in CONTAM(W) libraries and other variables were set accordingly. CONTAM(W) runs generated several concentration profiles for all the studied air pollutants. The corresponding health effects were addressed through the virtual concentration distribution inhaled by potential occupants of the modelled dwellings. The distribution profiles and the corresponding health effects were found to depend on (a) the amount of time which an exposed person would spend in a zone with a source of pollution, (b) the operation duration of the cuisine and the heater, (c) the weather parameters, (d) the indoor design of the dwelling, (e) the location of the source of pollution and the (f) size of the openings of the dwelling. The results indicated that the alteration of the baseline levels of the CONTAM(W) parameters affects the distributions and the modelled health effects.

Keywords: CONTAM(W); IAQ; Modelling; Indoors

Introduction

When alternative methods for heating and cooking are utilised indoors and the combustion of different kind of fuels is included, a number of pollutants are produced depending on the fuel type [1,2]. This phenomenon is called Household Air Pollution (HAP) and is responsible for more than 4 million deaths annually [3]. Heaters that use biomass, butane, Liquid Petroleum Gas (LPG) and kerosene, fireplaces and wood – burning stoves are some examples of alternative methods for energy. The reason for studying different ways of producing energy is to understand how the behaviour of indoor air is altered correlated to the air produced by the combustion [4,5]. This means that as long as heaters or stoves are used, a large number of air pollutants are produced and get combined with the existing air [6]. Some of the pollutants produced, among many, are the formaldehyde (CH_2O), the carbon monoxide (CO), the nitrogen dioxide (NO_2), the particulate matter ($PM_{2.5}$) and the nitrogen oxides (NO_x) [7-10]. Another significant pollutant that is naturally produced and extensively studied for HAP, is radon (^{222}Rn). Radon originates from the soil and underlying rock and it enters the buildings through cracks, pipelines, sinks, etc [11]. According to the U.S Environmental Protection Agency (EPA) and the International Agency for Research on Cancer (IARC) radon alongside formaldehyde have both been established as Group 1 and Group A carcinogens with deadly potential effects on human health that usually target the respiratory system. For this reason the World Health Organization has set threshold values for formaldehyde concentration that may not exceed 0.1 mg/m^3 or 0.08 ppm [12] and concerning radon, the EPA suggests concentration levels between 2-4 pCi/L [13] although the WHO suggests concentrations the least possible [14]. The objectives of the present work were (a) to study the concentration levels of selected air pollutants inside dwellings; (b) to compare these concentration levels to the threshold values from WHO and EPA and (c) to exhibit the burden that two occupants may receive throughout a time schedule in specific period of the year. The objectives were implemented through CONTAM(W).

Materials and Methods

The study was divided in two sets of modelling approaches: (a) model two dwellings with different parameters among them and (b) model one more dwelling and exhibit the inhaled CONTAM(W)-dose between two virtual occupants after an increase in the generation rate of the contaminants under investigation. The modelled dwellings were idealised according to the Greek situation, namely they were created based on the typical Greek apartments of Athens. These were then described and modelled via CONTAM(W). These apartments had average insulation based on the scale of CONTAM(W) for openings created by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) [15]. For the needs of cooking a town gas cuisine (also known as coal gas) was described and for the needs of heating a kerosene space heater. The specifications of the town gas cuisine and the kerosene space heater were obtained from a database that was designed by the National Institute of Instruments and Technology (NIST) for CONTAM(W). In general the way of producing pollutants throughout a zone was the constant coefficient model of CONTAM(W). The formula that explains this model is S=G-D·S, where G is the generation rate calculated in a mass of contaminant, D is the removal rate calculated in a mass of air and C is the temporal concentration of the mass of the contaminant per unit mass of air [16].

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First modelling approach

For the both modelled dwellings, the generation rate of the pollutants remained unchanged. Table 1 shows the employed generation rate values of the investigated pollutants.

Parameters of dwelling 1: The model of the first dwelling is depicted in Figure 1. It consisted of five zones: (a) a living room of 20 m^2, (b) a 10 m^2 kitchen, two bedrooms with floor area of (c) 9 m^2 and (d) 8 m^2 each and (e) one bathroom with space of 4 m^2 The heating source was set in the living room and the cooking source in the kitchen.

Every room was modelled as having two openings: a door and a window except living room which had an additional door that served as the doorway and kitchen which was modelled as having an additional door connecting to the exterior. The parameter that affected the amount of air transposed from one zone to another was the discharge coefficient which is a value that usually ranges from 0 to 1. Note that the insulation of the opening is improved as long as the value of the discharge coefficient is closer to 0. The adopted value of the discharge coefficient for doors and windows connected to the exterior was 0.7, while the corresponding value for the openings indoors ranged from 0.65 to 0.75. From the list of the weather parameters available to CONTAM(W), the ones selected with greater concern were (a) the temperature, (b) the absolute pressure, (c) the relative humidity and (d) the wind speed. The weather conditions were set for a cold Greek climate, viz., the early days of December, and for this reason the ambient temperature of the modelled dwelling was considered to be of a mean value of 10°C, the relative humidity approximately equal to 20%, the absolute pressure equal to 101325 Pa and the wind speed of 15 m/s. Because of the cold climate parameters, a related schedule was created and added to CONTAM(W) in order to fulfill the necessity for heating. The heating hours were considered to be during afternoon and, more specifically, between the hours of 7 p.m and 10 p.m which hypothetically is the period of the time where occupants reside inside the house. A schedule of cooking was additionally created in the morning hours between 9 a.m and 11 a.m. The heating schedule increased the indoor temperature to 21°C in living room and kitchen and to 20°C in the rest rooms.

Parameters of dwelling 2: The second modelled dwelling is shown in Figure 2. The space of each zone of has been grown in respect to the one of the first modelling approach. More specific: (a) the kitchen's zone was grown up to 12 m^2, (b) the living room to 25 m^2, (c) the first bedroom to 12 m^2, (d) the second bedroom to 10 m^2 and (e) the bathroom's space to 7 m^2.

Note that the position of the source of pollution is different in respect to dwelling 1, but remained in the same zone as in the first dwelling. The discharge coefficient values of the openings were the same with those of dwelling 1. As for weather parameters, the temperature was reduced to 5°C, the relative humidity to 15% while the wind speed was increased to 20 m/s which translates to generally slight colder weather conditions. The same schedules for heating and cooking were followed as the ones of the first dwelling.

Second modelling approach

A third modelled dwelling was employed in this approach. It consisted of 5 zones: (a) a kitchen of 10 m^2 space, (b) a living room of 20 m^2 space, (c) a large bedroom of 9 m^2 space, (d) a smaller bedroom with space of 8 m^2 and (e) a bathroom with space of 4 m^2. Figure 3 exhibits the floor plan of this dwelling. In the center of the model, the two circles represent the occupants although they behaved according to a specific schedule and they did not reside in the dwelling 24 hours a day. The additional contamination source in the kitchen and bathroom, referred to radon [17].

Concerning weather parameters, the temperature of the building was at 10°C, the absolute pressure was assumed equal to 101325 Pa, the relative humidity to 20% and the wind speed was to approximately 15 m/s. The weather parameters predisposed a cold climate and more specific, early days of December. There also existed a schedule for heating and cooking: the cooking was carried out in the morning hours especially from 9 a.m to 11 a.m while the heating schedule worked in the afternoon, from 7 p.m to 10 p.m. The heating schedule raised the indoor temperature to 21°C in living room and kitchen and to 20°C in the rest rooms.

The occupants were scheduled as well in order to perform as much as possible to actual conditions of Greece. The first occupant was scheduled to be absent from the dwelling during the morning hours, 8 a.m to 18 p.m and to return afterwards. The second occupant was scheduled to be inside the dwelling and perform indoor activities including the process of cooking but from 4 p.m until 7 p.m the occupant was absent and returned afterwards. As a consequence of the schedules, only one occupant was exposed to air pollution from the cuisine and the space heater. The inhalation rate was assumed equal to 5.1×10^{-3} m^3/min which is the average ventilation rate of humans between age 21 and 31 while doing passive activities and being non-smokers [18].

Results

For every model described, the concentration graphs were extracted for each one of the investigated pollutants in each zone although only the ones worth exhibiting are represented in this work. Note that the CONTAM(W) graphs represent the amount of each pollutant under investigation in each room while the kerosene space heater and the town gas stove operated on scheduled times. Each room is plotted in a specific color: red was used for the first bedroom, brown for the kitchen, light green for the second bedroom, light blue for the living room and dark blue for the bathroom.

Figures 4 and 5 present the distribution of Carbon Monoxide in dwellings 1 and 2 respectively. In the first modeled dwelling, the maximum value was observed in the kitchen, at 15.4 ppm, while the least possible value was observed in the second bedroom with a value of 0.8 ppm in the evening hours. In the second dwelling and during exactly the same scheduled hours, the maximum value was observed in the living room with a value of 3.2 ppm while the minimum value was approximately 0.7 ppm. The concentration of the kitchen though remained high compared to the other rooms; 2.2 ppm the lowest and 2.4 ppm the highest values. In general, the carbon monoxide concentration was reduced from (mean ± standard deviation) (2.71 ± 3.28 ppm) to (1.49 ± 0.76 ppm).

Figures 6 and 7 present the distribution of formaldehyde in dwellings 1 and 2 respectively. The first dwelling, exhibited remarkably high concentration values of inside the kitchen when compared to the corresponding ones of the other four rooms. More specifically, the kitchen's concentration varied from 1 mg/m^3 to 2.7 mg/m^3, while the concentration in the remaining rooms varied from 0.18 mg/m^3 to 0.3

Cooking (mg/s)		Heating (mg/s)	
CH_2O	0.11	CH_2O	0.4
CO	0.75	CO	5.4
NO_2	0.68×10^{-3}	NO_2	4.2×10^{-3}
NOx	1.4	$PM_{2.5}$	19×10^{-3}

Table 1: Employed generation rate values of the investigated pollutants.

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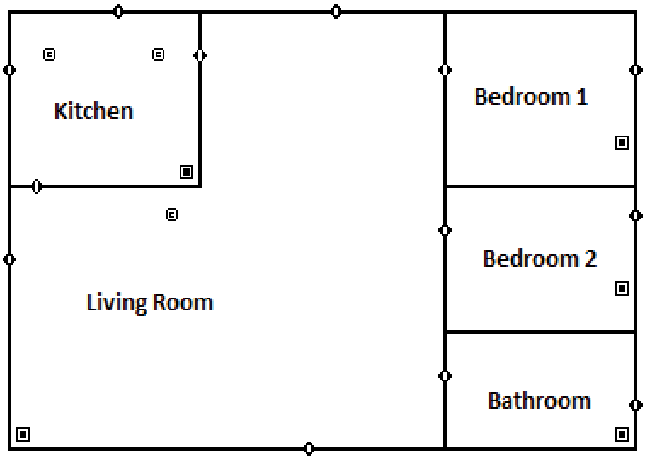

Figure 1: First building's floor plan. The open circles represent the window and the door openings. The filled squares show the contamination sources.

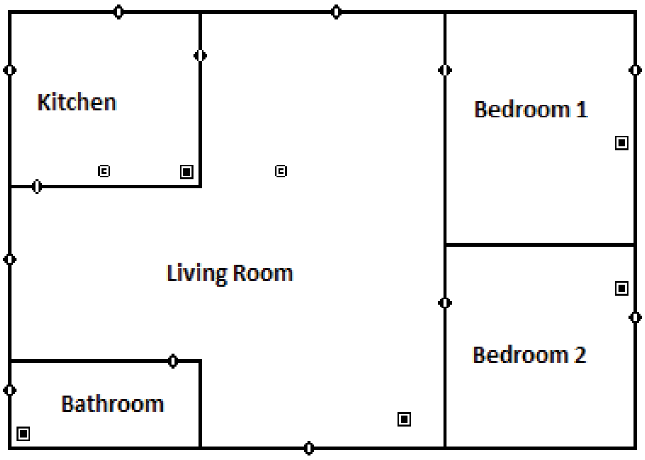

Figure 2: Second building's floor plan. The open circles represent the window and the door openings. The filled squares show the contamination sources.

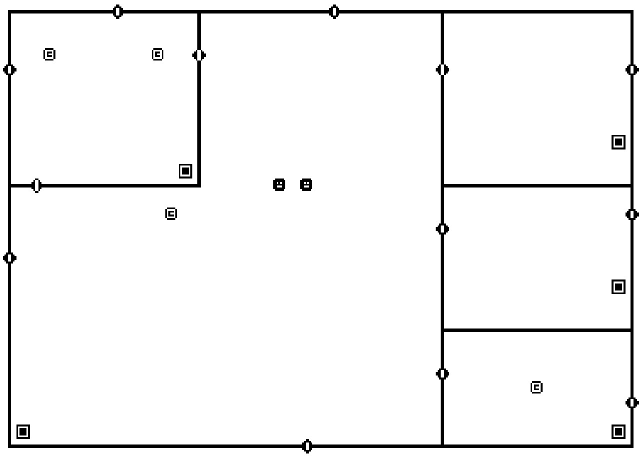

Figure 3: Floor plan of the dwelling of section 2.2. The circles attached to the lines represent the openings and the squares show the contamination sources.

mg/m³. In contrast to the first dwelling, the second dwelling's values were lower. The maximum value was 0.4 mg/m³ and was observed in the kitchen, while the minimum value was 0.06 mg/m³ and was observed in the second bedroom. The average concentration value was reduced from (mean ± standard deviation) (0.39 ± 0.63 mg/m³) to (0.15 ± 0.1 mg/m³).

Figures 8 and 9 show the corresponding results regarding nitrogen dioxide. In detail, the kitchen showed the highest values, between 6.2 μg/m³ and 16.4 μg/m³ and the next nearest concentration was observed in the living room, ranging from 1.8 μg/m³ to 3.2 μg/m³. In the second dwelling the highest value was observed in the living room, with a corresponding value of 2.78 μg/m³. The bathroom exhibited greater concentration values compared to the two bedrooms with average value of 1.05 μg/m³. The overall average concentration was reduced from (mean ± standard deviation) (2.58 ± 3.56 μg/m³) to (1.38 ± 0.71 μg/m³).

The last modelled contaminant group of the first modelling approach referred the particulate matter $PM_{2.5}$ (Figures 10 and 11). The kitchen concentration levels were almost zero due to the fact that no $PM_{2.5}$ were produced while the town gas cuisine operated. The graphs showed that concentration on all rooms remained stable for the operation schedule of the model. In detail, in the first dwelling, the living room had average concentration of 15 μg/m³ and the bathroom had average concentration of 8.5 μg/m³. Likewise in the first dwelling, the second dwelling also showed steady concentrations but slightly reduced. In particular, the living room had average concentration of 12.5 μg/m³ and the bathroom followed with concentration values of 6.5 μg/m³. The mean concentration was reduced from (mean ± standard deviation) (9.75 ± 3.05 μg/m³) to (7.63 ± 2.84 μg/m³).

For the second modelling approach, the results are presented before and after a virtual increment of 50% from their baseline values. Table 2 shows the generation rate values for radon and formaldehyde before and after this virtual 50% modelled increment.

Figure 12 shows the results for formaldehyde. The highest concentration was observed in the kitchen with value of 0.095 mg/m³ and the least possible value was observed in the second bedroom with value of 0.015 mg/m³. After the random increase, the highest value came up from the kitchen with concentration of 0.142 mg/m³ which exceeds the threshold value that was set from the WHO by 0.042 mg/m³. The average concentration in the kitchen was 0.097 mg/m³ and in the living room 0.036 mg/m³. The overall average was (mean ± standard deviation) (0.019 ± 0.02 mg/m³) before the increment and (0.03 ± 0.03 mg/m³) after which is 36% higher. In Figure 12 the exact results can be observed.

The average concentration levels on the first occupant had a value of 0.047 mg/m³ which is 31% higher than the concentration value of 0.032 mg/m³ before the increment and 36% higher compared to the overall concentration of the dwelling. The second occupant had average concentration of (mean ± standard deviation) (0.041 ± 0.04 mg/m³) and compared to the exact results before the increase (mean ± standard deviation) (0.028 ± 0.02 mg/m³), the concentration has been increased by 31.7%. Figures 13 and 14 show the inhalation CONTAM(W)-doses (concentration inhaled) that the occupant would receive after the 50% increment of the pollutants.

Figure 15 presents the corresponding results of radon. The radon results showed that the zones with the highest concentration had an existing source of radon. More specifically, the highest value was observed in the kitchen, 80 Bq/m³ while the lowest was observed in the second bedroom with value of approximately 2 Bq/m³. The average concentration in the kitchen was (mean ± standard deviation) (32.37

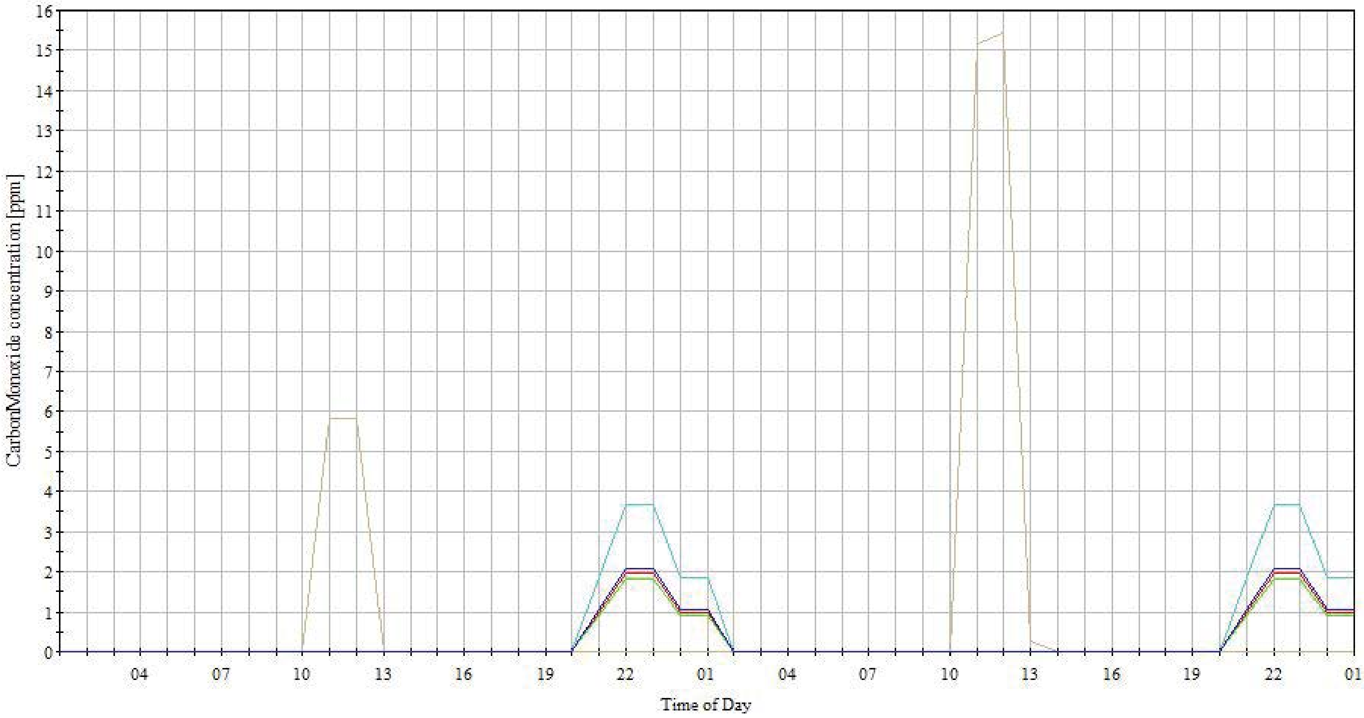

Figure 4: CO concentration in the first dwelling.

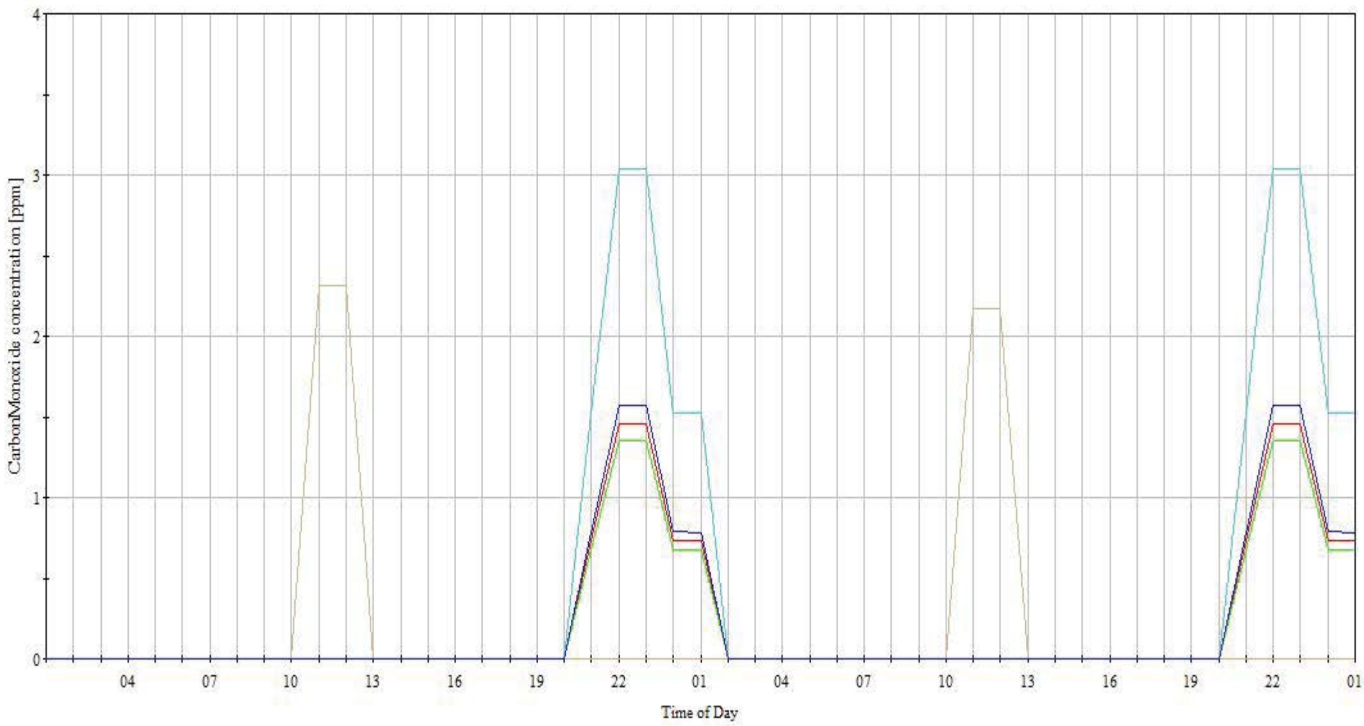

Figure 5: CO concentration in the second dwelling.

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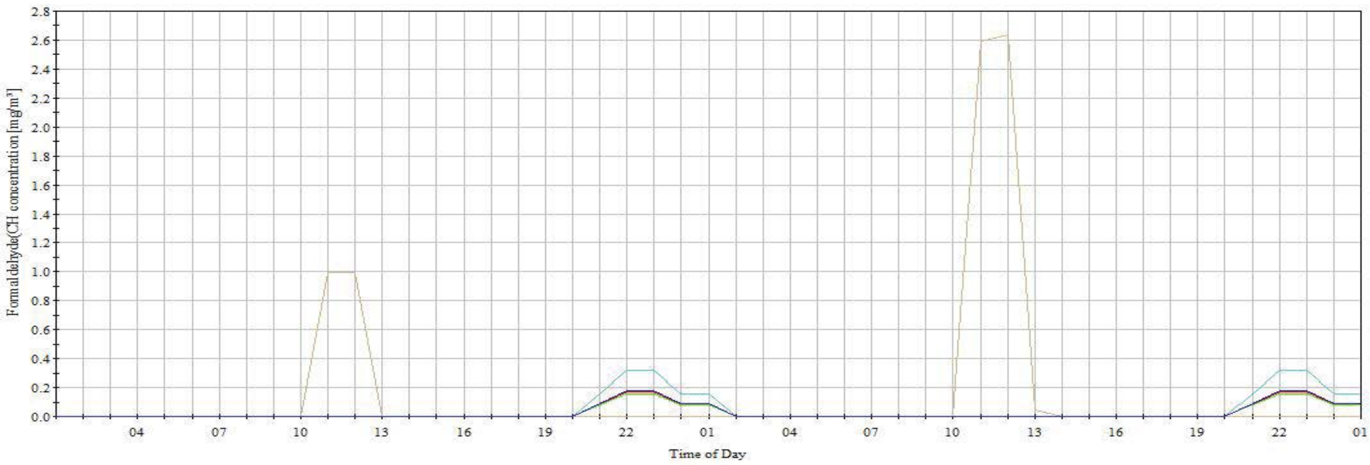

Figure 6: CH_2O concentration in the first dwelling.

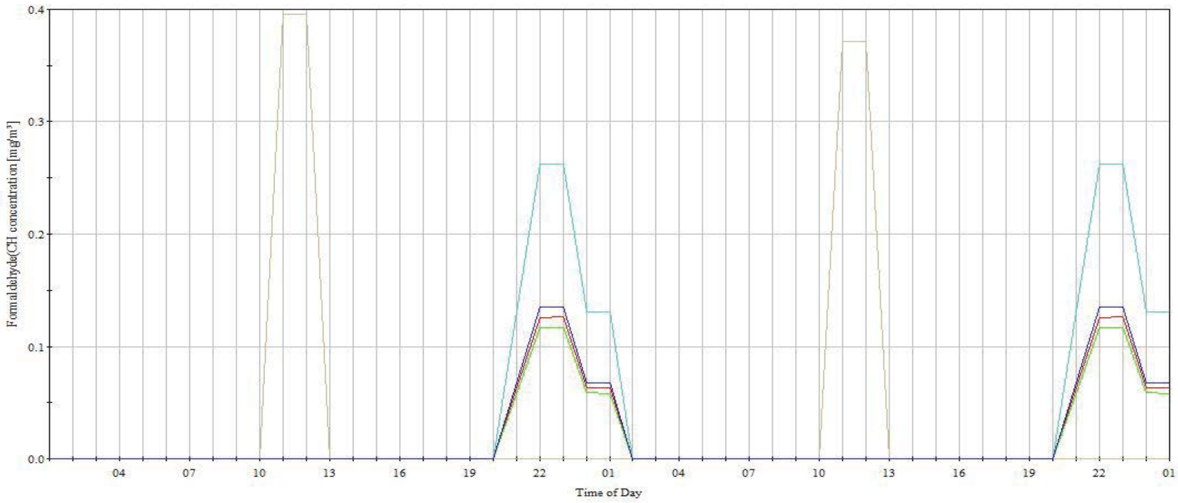

Figure 7: CH_2O concentration in the second dwelling.

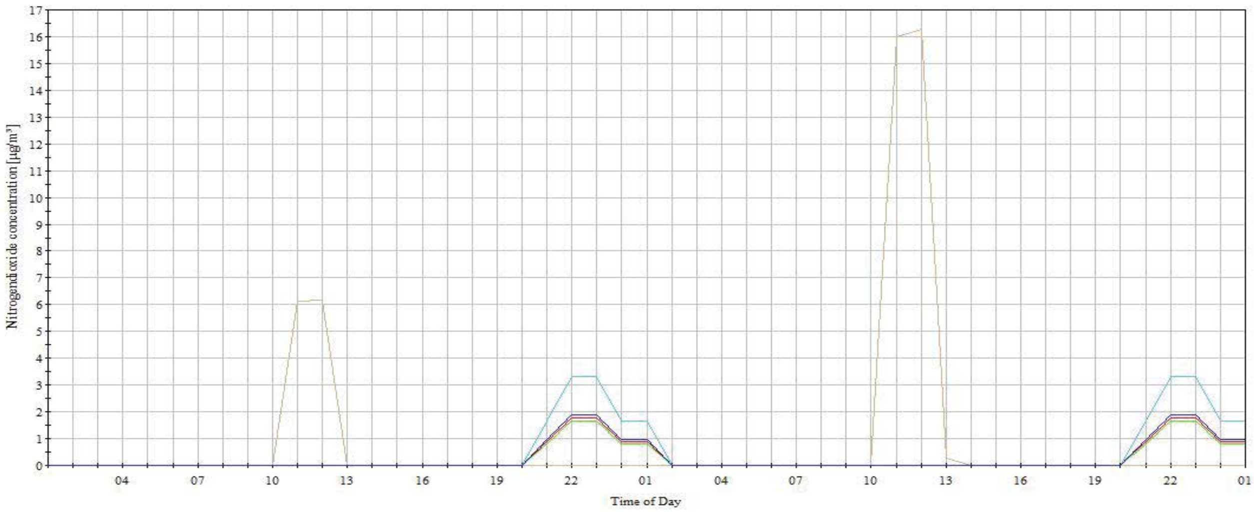

Figure 8: NO_2 concentration in the first dwelling.

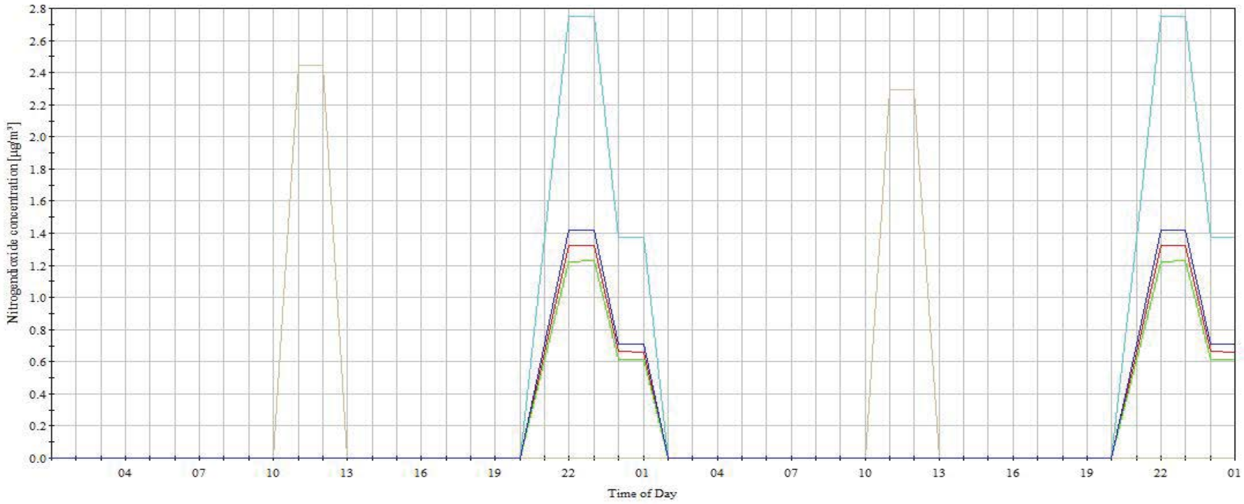

Figure 9: NO_2 concentration in the second dwelling.

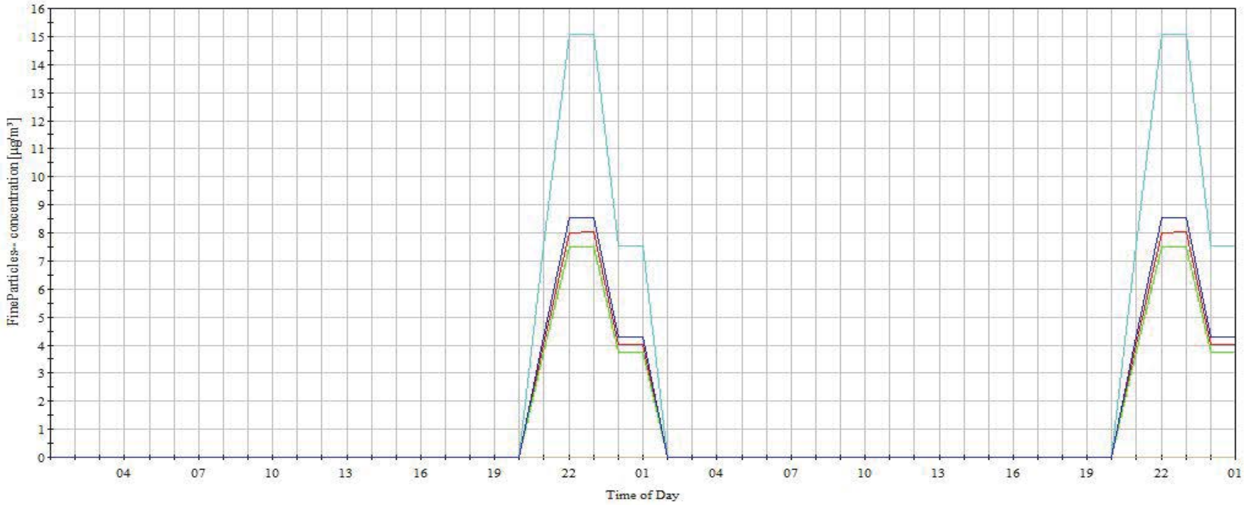

Figure 10: $PM_{2.5}$ concentration in the first dwelling.

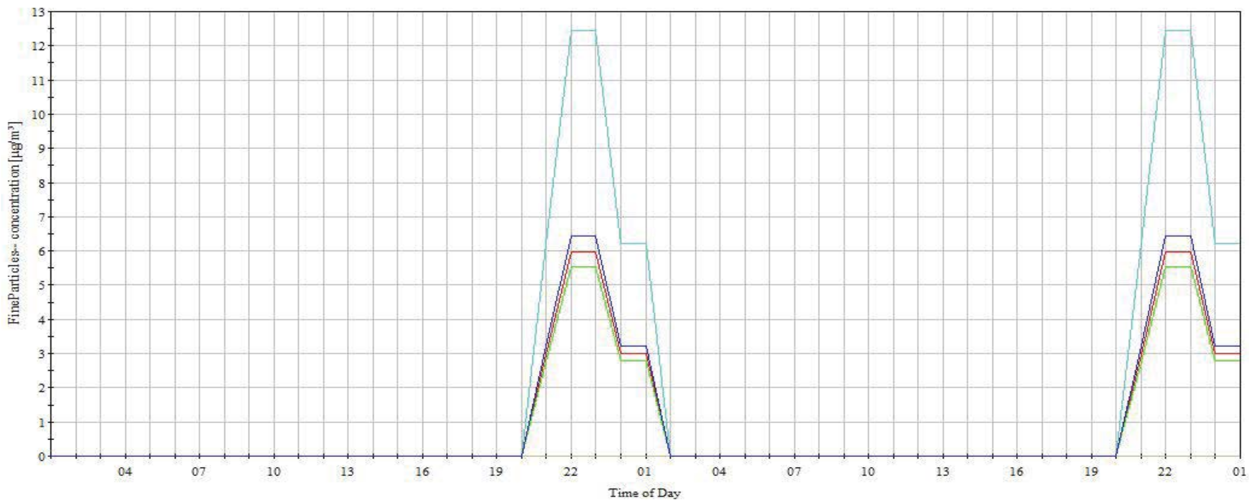

Figure 11: $PM_{2.5}$ concentration in the second dwelling.

Contaminant	Generation rate (before the increment)	Generation rate (after the 50% increment)
CH_2O (cooking) (mg/s)	0.004	0.006
CH_2O (heating) (mg/s)	0.04	0.06
^{222}Rn (Bq/h)	12,000	18,000

Table 2: Generation rates of radon and formaldehyde before and after a virtual 50% increase (column 3) from their baseline values (column 2).

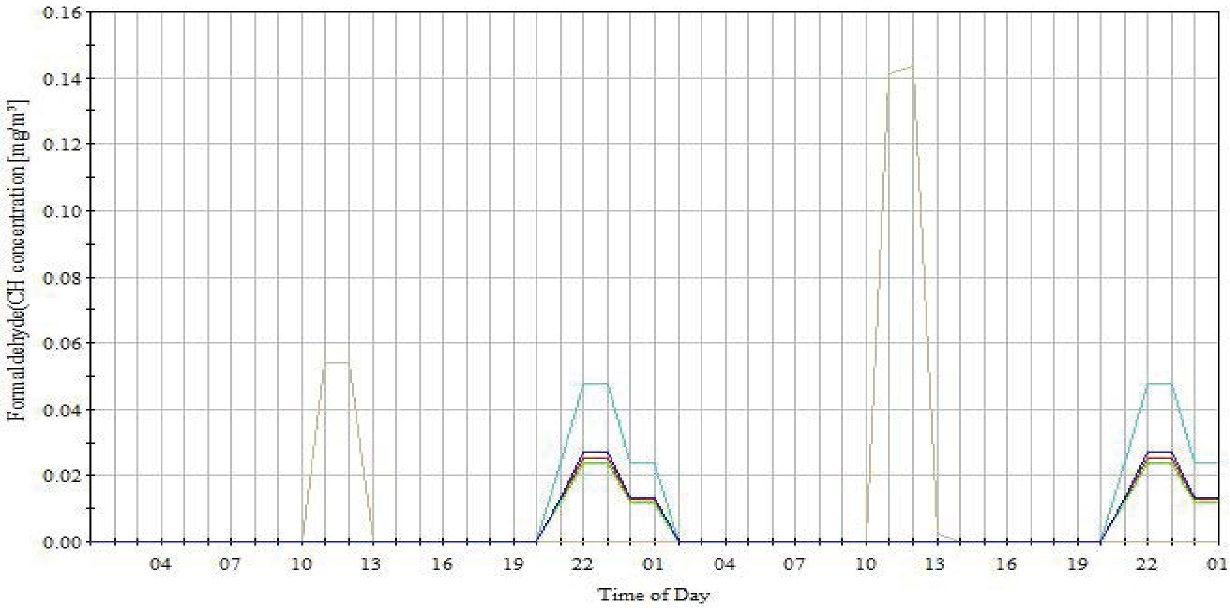

Figure 12: Formaldehyde concentration after the 50% virtual increase of Table 2.

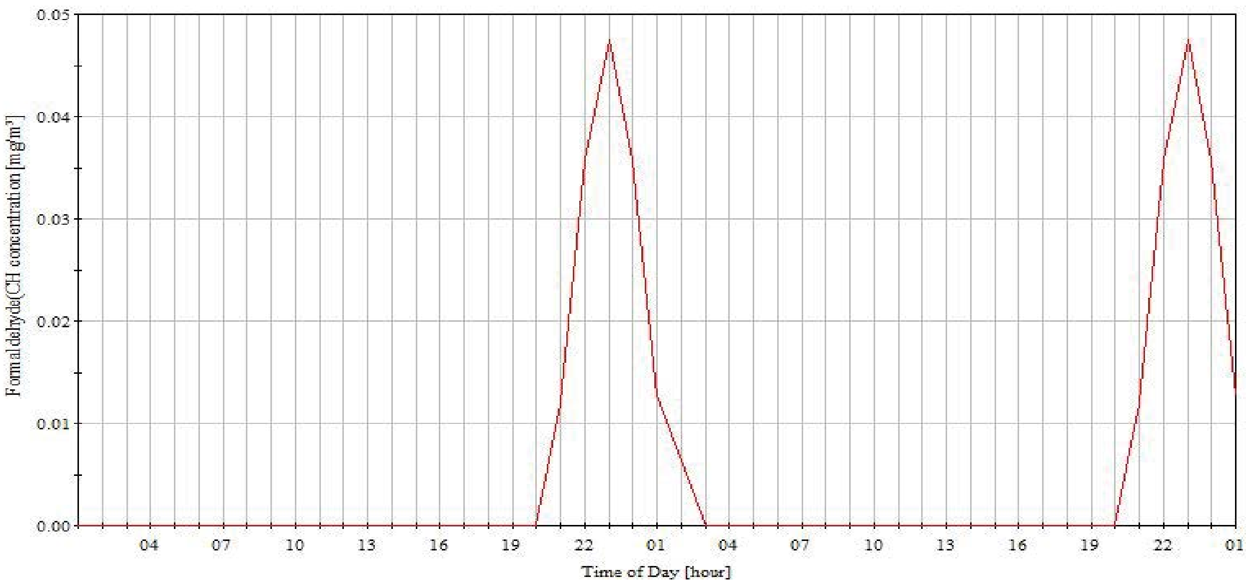

Figure 13: Formaldehyde CONTAM(W)-doses (inhaled concentration distribution) for the first occupant after the 50% virtual increase of Table 2.

± 24.2 Bq/m³) and the average concentration in the bathroom was (mean ± standard deviation) (30.37 ± 7.1 Bq/m³). The overall mean concentration came up to (mean ± standard deviation) (16.52 ± 13.6 Bq/m³). After the increase the two zones with the highest average concentration were the kitchen and the bathroom with values of (mean ± standard deviation) (49 ± 36.55 Bq/m³) and (mean ± standard deviation) (40.25 ± 11.24 Bq/m³) respectively. The percentage increase on these two zones is calculated to 33.9% for the kitchen and 32.5% for the bathroom. The overall mean concentration came up to (mean ± standard deviation) (19.34 ± 18 Bq/m³) which is 17% higher compared the values before the increment. In Figure 15 the results after the increase are shown.

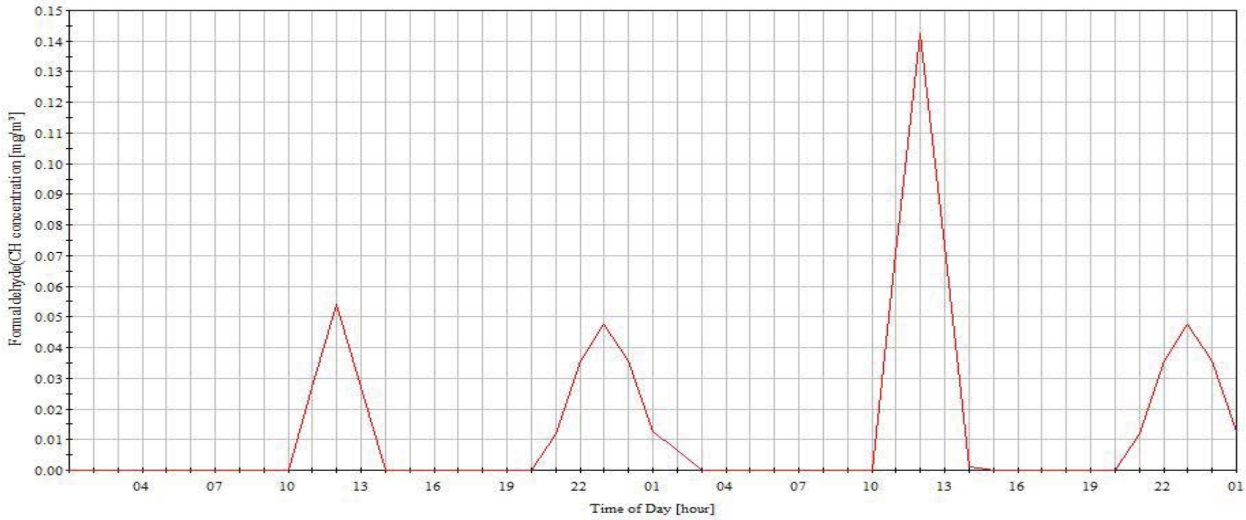

Figure 14: Formaldehyde CONTAM(W)-doses (inhaled concentration distribution) for the second occupant after the 50% increase of Table 2.

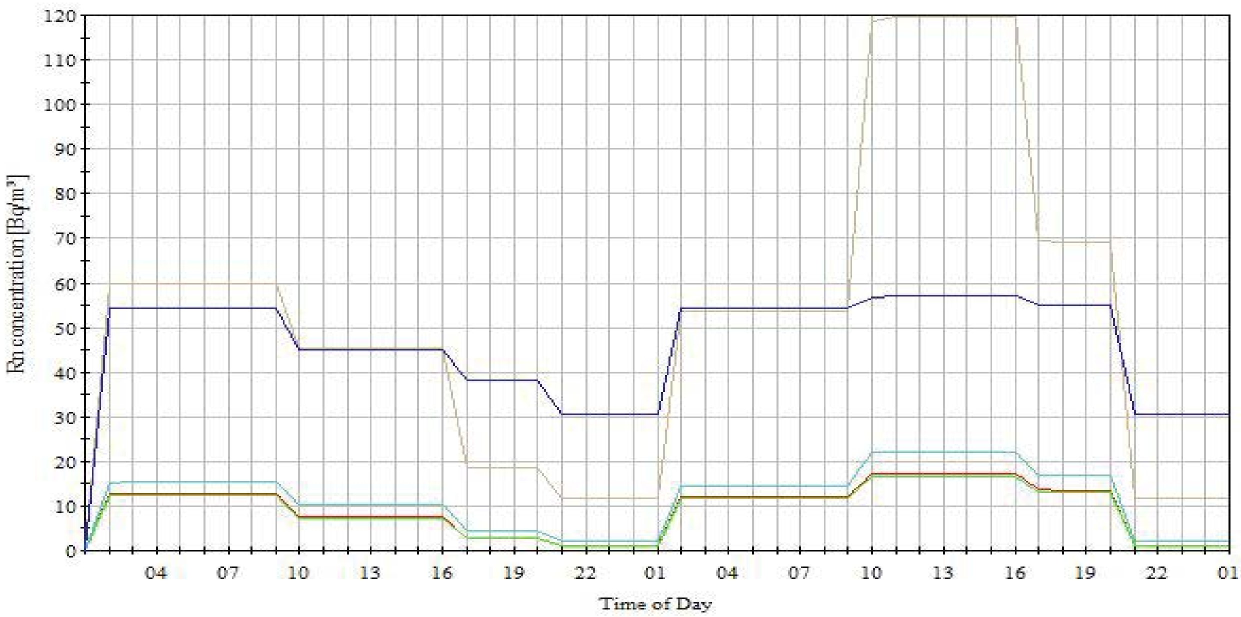

Figure 15: Radon concentration results after the 50% increase of Table 2.

Regarding the first occupant (Figure 16), the concentration peaked in the morning hours due to the 30 minute presence in the kitchen. The highest value was approximately 46 Bq/m^3 and the lowest was about 3 Bq/m^3. The overall concentration amounted to (mean ± standard deviation) (18.8 ± 17.7 Bq/m^3) which is 13.8% increased compared to the overall average value. For the second occupant the maximum value observed is 80 Bq/m^3 and the least possible 2 Bq/m^3. The mean concentration for each of two consecutive days is (mean ± standard deviation) (19.3 ± 24.5 Bq/m^3) which exceed the overall concentration of the zones by 14.4%. After the increase, the mean concentration for the first occupant was (mean ± standard deviation) (29.25 ± 27.15 Bq/m^3) which is increased by 55.5%. The second occupant (Figure 17) also developed similar behaviour compared to the results before the increment but with higher values. The mean concentration came up to (mean ± standard deviation) (30 ± 39.3 Bq/m^3) which increased by 55.4% compared to the value before the random increase.

Discussion

Regarding the first modelling approach where the generation rate of the contaminants and the discharge coefficient value of the openings remained unchanged, it was found that the climate change affects directly the concentration levels. More specifically, the carbon monoxide had a reduction of 45%, the formaldehyde was reduced by 61.5%, the nitrogen dioxides were reduced by 46% and finally the particulate matters made the least possible reduction with a value of 21.7%. Table 3 shows the first and second dwelling averages as well as the percentage reduction for each pollutant.

In reference to the second modelling approach, where the climate

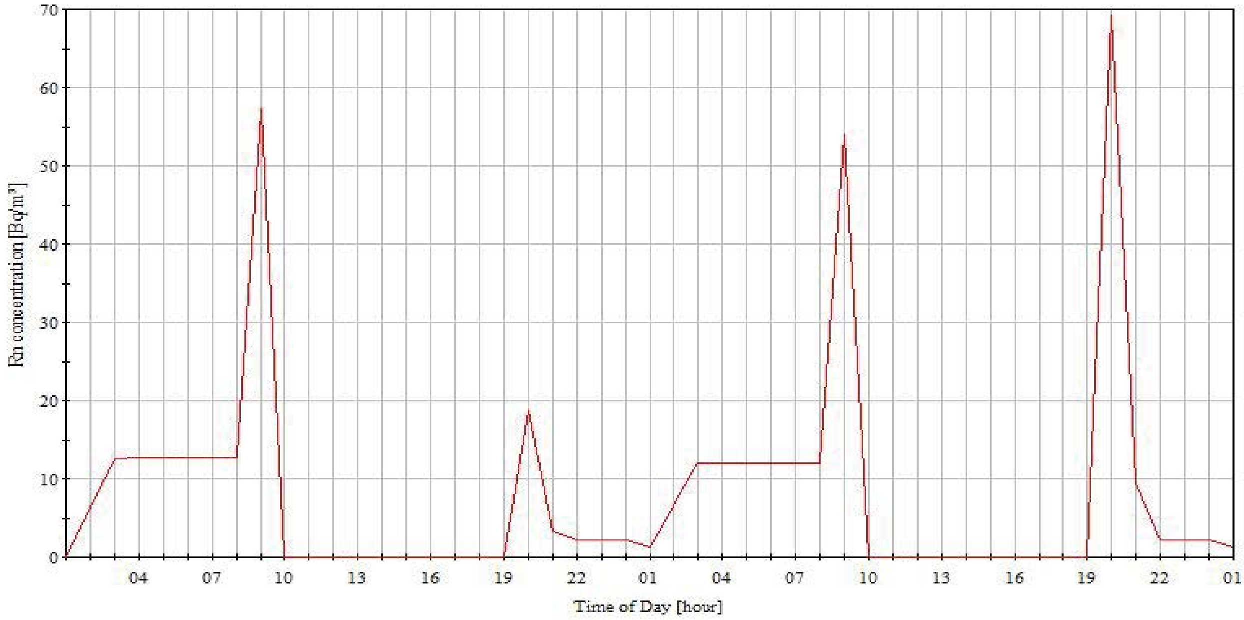

Figure 16: Radon CONTAM(W)-doses (inhaled concentration distribution) for the first occupant after the 50% increase of Table 2.

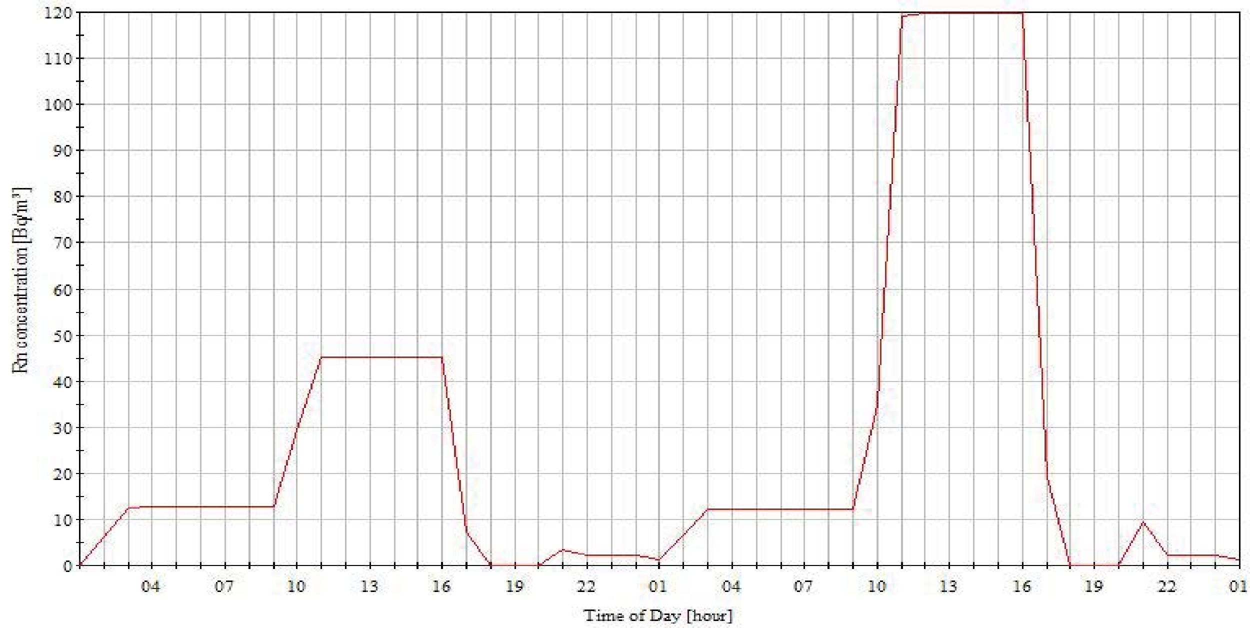

Figure 17: Radon CONTAM(W)-doses (inhaled concentration distribution) for the second occupant after the 50% increase.

parameters and the discharge coefficient remained unchanged, the increased generation rate of the contaminants was a determinant factor. To be more specific a 36% formaldehyde increase in the zones led to a 36% increase in the inhaled dose for the first occupant and to a 31.7% for the second occupant. Regarding radon a 17% increase in the zones led to a 55.5% increase in the inhaled dose for the first occupant and 55.4% for the second. It is clear that the radon increase ratio is due to the fact that the cracks inside the building operate throughout the day and not for specific hours of the day. The summarized results are given in Table 4.

According to WHO, the concentration levels of Carbon Monoxide must be kept below 8.73 ppm in an 8-hour of exposure. The concentration levels of CO in the first set of measurement were within the WHO limits (Table 3). The formaldehyde threshold values must be kept below 0.1 mg/m^3, which contraries the addresses concentration values of both dwellings since (mean ± standard deviation) (0.39 ± 0.63 mg/m^3) was found for the first dwelling and (mean ± standard deviation) (0.15 ± 0.1 mg/m^3) for the second modelling approach. The concentration of the second dwelling was almost near to the threshold values of the WHO, but still remained in remarkably high levels so as the human health is secured. The particulate matters with diameter of 2.5 micrometers were produced only in the evening hours and, thus, it was

	1st dwelling Average	2nd dwelling Average	Percentage Reduction
CO	2.71 ± 3.28 ppm	1.49 ± 0.76 ppm	45%
CH_2O	0.39 ± 0.63 mg/m^3	0.15 ± 0.1 mg/m^3	61.5%
NO_2	2.58 ± 3.56 μg/m^3	1.38 ± 0.71 μg/m^3	46%
$P.M_{2.5}$	9.75 ± 3.05 μg/m^3	7.63 ± 2.84 μg/m^3	21.7%

Table 3: Summary table for the first modelling approach.

	Formaldehyde	Formaldehyde (+50% increase)	Percentage	Radon	Radon (+50% increase)	Percentage
Zones	0.019 ± 0.02 mg/m^3	0.03 ± 0.03 mg/m^3	+ 36%	16.52 ± 13.6 Bq/m^3	19.34 ± 18 Bq/m^3	17%
1st occupant	0.032 mg/m^3	0.047 mg/m^3	+36%	18.8 ± 17.7 Bq /m^3	29.25 ± 27.15 Bq/m^3	55.5%
2nd occupant	0.028 ± 0.02 mg/m^3	0.041 ± 0.04 mg/m^3	+ 31.7%	19.3 ± 24.5 Bq /m^3	30 ± 39.3 Bq/m^3	55.40%

Table 4: Summary table for the second set of measurements for Radon and Formaldehyde.

the pollutant with the slightest reduction. The WHO terms maximum threshold values at approximately 25 μg/m^3 for daily exposures. Both dwellings were within the WHO limits. The NO_2 concentration levels must be kept below 40 μg/m^3 which has been achieved for both dwellings of the first set of measurements [14]. Regarding the second modelling approach, high concentration peaks were observed in the second day in the kitchen with values that reached and exceeded the guidelines of the WHO and the EPA. Formaldehyde concentration in the kitchen reached 0.142 mg/m^3 and radon reached the value of 120 Bq/m^3 [14].

Conclusions

This paper was a first systematic attempt to model with CONTAM(W) some air pollutants of noteworthy interest for the human health for Greece. The air pollutants that were investigated were the carbon monoxide (CO), the nitrogen dioxide (NO_2), the particulate matter ($PM_{2.5}$, Radon (^{222}Rn) and Formaldehyde (CH_2O).

The results indicated that the health burden from the investigated air pollutants depends mainly depending on (a) the generation rate period and (b) the duration in which an occupant inhales a certain pollutant. The CONTAM(W)-doses, namely the concentration distribution inhaled by the occupants, were found to depend on six partial parameters: (a) the amount of time in which the exposed person resides in the zone with the source of pollution, (b) the operation duration of the cuisine and the kerosene heater, (c) the weather parameters, (d) the indoor design of the zones of the dwelling, (e) the location of the source of pollution and the (f) size of the openings of the dwelling. The alteration of the above factors affects the indoor air quality of the dwelling and, in this manner, the concentration profiles of the indoor air pollutants. Although the formaldehyde concentration levels can be lowered by taking into account the parameters mentioned above, radon may need extensive methods due to the fact that a great percentage of radon in dwellings enter through natural pathways.

Future work will extend the investigation to other air pollutants and different scenarios of heating and pollutant transfer paths. It is intended to model more dwellings similar to the usual Greek buildings. Focused investigation is planned in certain test dwellings with a combination of modelling and measurements.

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