Life cycle assessment of concrete production with a focus on air pollutants and the desired risk parameters using genetic algorithm

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Abstract

Background Through a new systematic perspective, the HSE-integrated management system attempts to examine the relationships between safety, health and environment. The purpose of this system is to provide a coordinated, comprehensive and precautionary assessment of the issues and incidents within concrete plants.

Methods In addition to a life cycle assessment (LCA) of concrete through air pollutant emissions in this study, the extraction and monitoring of pollutant from three concrete plants in the city of Mashhad are carried out via fieldwork. In the present study, a number of factors such as the extent and time of exposure to each pollutant are estimated using the meta-heuristic genetic algorithm approach (GA) in order to create the desirable risk rate (risk rate ≤ 3).

Results The results of life cycle assessment indicate the production of 348 kg Carbon Dioxide (CO₂) per cubic meter of concrete processing. However, in addition to its environmental effects, CO₂ in concentrations of more than 5000 ppm may cause asphyxiation as well as epidemiologic effects on the staff.

Conclusion The results of the study show that in order to reduce the risks of developing chronic diseases such as lung cancer, the staff in cement processing sector must be exposed to a period of at most 3.5 h for each 8-h work interval.

Keywords Concrete · Air pollution · Life cycle assessment · Genetic algorithm

Background

One of the most important and essential issues concerning the maintenance of safety and health in workplaces are monitoring and controlling air pollutions. Epidemiologic investigations show that the short-term effects of air pollution include changes in lung functions, shortness of breath symptoms, lethargy, dizziness and imbalance [1]. Furthermore, air pollution causes chronic symptoms in long-term, some of which may

include lung cancer, asthma, allergy and chronic obstructive pulmonary [2]. Iran, as one of the developing countries, has been witnessing significant activities regarding building constructions. One of the key units in the building industry is concrete plants which are considered as inseparable component of executive processes in building construction, both in structural and non-structural phases. It must be pointed out that, based on structural calculations and non-structural details, different buildings may use various amounts of concrete. Studies on concrete implementation have shown that such component can be provided either by preparation within the construction site or through processing in factories. Yet, the second approach, i.e. concrete processing in factories, has been more common while meeting concrete standards more prominently [3]. Production of concrete involves a set of chemical processes during which gaseous pollutants and particles such as carbon dioxide (CO₂), sulfur dioxide (SO₂), volatile organic compounds (VOCs), carbon mono oxide (CO), nitrogen oxides (NO_x) and particle matter (PM₁₀, particles with a diameter of less than 10 μ m) are produced [4]. It should be noted that during operations of transportation and shipping of concrete, in addition to the abovementioned

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pollutants, methane gas (CH_4) is also spread around the environment [5]. The investigation of threatening risks for health and epidemiologic effects produced by pollutants on the staff, engineers and every individual who is exposed to such pollutions for hours on a daily basis, are the focus of the present study.

Gauderman et al. (2000) conducted a study on the effects of nitrogen dioxide (NO_2) and mercury acid vapor. The study demonstrates the substantial effects of the above pollutants on the efficiency of pulmonary system in human body [6]. Based on World Health Organization (WHO) reports in 2008, more than 160 million workers encounter accidents, injuries and occupational complications each year [7]. Torén et al. (2007) investigated the effects of exposure to air pollution and deaths caused by different ischemic heart and cerebral diseases in work environments. This study focused on the effects of consumable materials in construction industry, especially dust resulted from cement and concrete processing operations [8]. Kumar et al. (2016) assessed the cycle of eco-friendly material in the buildings located in Western Australia. The study is conducted with more focus on energy extraction and its retrieval in green buildings [9]. Using a framework, i.e. life cycle assessment method, Smith et al. (2007) investigated the function of concrete in designing pavements. In addition to areas concerning energy, the mentioned study has also taken air and water pollutions after the implementation of blocks into consideration [10].

Employing the life cycle assessment along with ecology risk assessment (EcoRA) method, Barna et al. (2007) have examined the environmental risks resulted from mineral waste. In this study, a number of administrative options derived from risk assessment are presented at local and international levels [11]. In another research conducted by Vieira et al. (2016), a study overview concerning life cycle assessment of concrete is presented. Life cycle assessment is carried out through four phases including production, usage, disposal and recycling. This study is conducted to provide a sustainable eco-friendly structure for typical and ecological concrete production [12]. Serres et al. (2015) have also attempted to study

life cycle assessment and environmental effects of the concrete which is produced from concrete waste. The study is carried out to draw an operational strategy to decrease environmental effects induced by the concrete [13]. Smailyte et al. (2004) evaluated mortality and incidence of cancer among cement production workers through another study in Lithuania. They considered Standardized Incidence Ratios (SIR) and Standardized Mortality Ratios (SMR) as the main measure of health status [14].

Using life cycle assessment method, Valipour et al. (2014) compared two kinds of concrete including concrete combined with zeolite and its common types. This study is conducted to investigate the environmental effects of global warming and pollutants [15]. In this regard, another study by Gursel et al. (2041) is carried out to assess the impacts of produced concrete life cycle (LCI) and determine its strengths and weaknesses. The purpose of conducting such a study is to improve the quality of produced concrete and reduce its destructive environmental impacts during concrete's life cycle [16]. In another library study by Laurent et al. (2014), 222 life cycle assessments concerning solid waste management (SWM) systems are examined [17]. Liu et al. (2017) assessed the environmental effects caused by CO_2 diffusion in road pavement project operations. In this study, 20 asphalt procedure projects as well as 18 concrete pavement projects were analyzed at two general levels of high-grade and low-grade roads [18]. In another study, Garcia et al. (2017) evaluated the environmental effects caused by residential unit repercussion using LCA technique. In this research, a number of 360 cases were studied with more focus on three phases of production, implementation and demolition [19]. Miller et al. (2016) offered mathematical models in concrete mix design. These predictive functions were presented with two objectives including desirable concrete resistance provision and global warming reduction (caused by concrete production process) [20]. Gursel and Ostertag (2016) also assessed the environmental effects caused by concrete production process in Singapore using the LCA method. This study has been conducted with two major goals of reducing energy consumption as well as

Fig. 1 Diagram showing the execution process of genetic algorithm regarding the optimization of *Risk Rate* problem

decreasing the production of gaseous pollutants, especially during the phases of cement processing [21]. Dong et al. (2015) quantified the environmental effects caused by concrete production based on databases in US PCA and Ecoinvent using Life Cycle Inventory (LCI) system in Hong Kong city [22]. Peters et al. (2009) also studied the effects of inhaling cement dust on construction workers. In this research, the combined approach of linear models was used to analyze distribution conditions of pollution [23].

Initially, the present study intends to analyze and calculate the air pollution produced by cement factory during the transportation of concrete to construction site using the LCA method. In the next step, it is attempted to analyze a single-objective equation from risk functions using meta-heuristic optimization algorithms with a new approach. In fact, the answers to the equation would indicate a set of parameters such as desirable concentrations of the produced pollutants within the environment of concrete plants as well as the extent of hourly exposure to the resultant concentration of pollutants to reach the acceptable risk rate.

Methods

The present research is a descriptive-analytical study which consists of two main sections: the first section includes life cycle assessment of air pollutants induced by concrete production and the second section involves safety indices. It is worth mentioning that in this study, in order to determine physical parameters such as workshop dimensions, the number of staff, arrangement and components of production process, approximate working hours, and the number of workers in each sector, data have been collected through fieldwork in three concrete production plants and workshops in the city of Mashhad including *Jahd Beton*, *Bonyan Beton*, and *Beton-e-Samen*.

Life cycle assessment with focus on air pollution

First, a comprehensive and classified databank containing information about concrete life cycle were examined which

Table 2 Different stages in concrete processing

Symbol	Stage
A	Transportation of raw material to cement and concrete plants
B	Internal transportation during the process of cement production
C	Cement production process
D	Transportation from cement plant to concrete plant
E	Internal transportation in concrete plant
F	Concrete production process
G	Other production processes of concrete

include: research and development studies (R&D) of PCA company (2008) [24], MIT University reports (2010) [25], studies conducted in Lund University of Sweden (2005) [26], research carried out in Stockholm University of Sweden (2011) [27] and reports of NRMCA company on sustainable structures (2001) [28]. The results of LCA analysis are represented as a tree diagram in Fig. 1. Interpretations of practical data were carried out in three concrete plants including *Jahd Beton*, *Bonyan Beton*, and *Beton-e-Samen*, the related information of which are represented in Table 1. In this research, risk analysis is separately evaluated in seven stages as described in Table 2.

Determining the safety parameters using the genetic algorithm method

At first glance, evolutionary algorithms seem to be a simple and basic mechanism, but their computing tools have an effective and adaptive system in search environments. Genetic Algorithm (GA) is also a member of the family of evolutionary systems. This computational model develops the possible responses as the chromosome with different genes in the search space and eventually reaches the most optimal and most appropriate values by evolving these responses. In fact, it should be noted that each chromosome contains a set of responses, which each of its sub-sections (genes) is the response of a section of the general objective function. The main function of evolutionary algorithms, i.e., meta-heuristic

Table 1 General characteristics of the studied units

Name of the industrial unit	Year of establishment	Number of staff active in site	Areas of production
Bonyan Beton	1991	20	Production of ready-mixed concrete, prefabricated concrete parts, and special concrete
Jahd Beton	1997	12	Prefabricated concrete parts, concrete products for various facilities and the production and implementation of ready-mixed concrete
Beton-e-Samen	1993	25	Production and processing of ready-mixed concrete and prefabricated parts

Table 3 Design of experiments in order to adjust genetic algorithm parameters using RSM technique

Level	Mutation rate	Cross over coefficient	Maximum iteration	Selection pressure	Initial population
1	0.1	0.7	100	5	50
2	0.2	0.8	300	10	100
3	0.3	0.9	500	15	150

algorithms, can be considered in problems in which the number of unknowns is greater than the number of equations. In this research, given that the studied factor is related to a function or the same function of the health risk rate; as well as, the number of unknowns is more than the number of equations, meta-heuristic algorithms and search systems have been applied to solve the problem.

The result of LCA analysis specifies the concentrations of pollutants such as CO, CO₂, SO₂, NO_x, PM₁₀ and VOCs

during the process of concrete production. Each of the pollutants creates a unique risk toward health at the workplace, the extent of which can be extracted from Eq. 1 [29]. In this part, the medium risk rate ($RR=3$) and the lesser values ($RR\leq 3$) are considered as the ideal situation, and the ultimate goal of determining M includes the extent of exposure in micrograms per cubic meter (W), average working hours in a week, and D , average time of each exposure (hourly) in desirable

Fig. 2 Life cycle assessment (LCA) with focus on production of air pollutants during the process of cement production

Fig. 3 Life cycle assessment (LCA) with focus on production of air pollutants during the process of concrete production

conditions. The inequality of ($RR \leq 3$) must be analyzed for every pollutant with genetic algorithm (GA).

$$\text{Risk Rate (Cost Function)} = \sqrt{HR_i \times ER_i} \quad (1)$$

$$ER_i = f(E_i), \quad E_i = \frac{M_i D_i F}{W_i}$$

$$E_{\text{combine}} = \sum_{i=1}^7 \frac{E_i}{PLE_i} \quad i = CO, SO_2, NO_x, CO, PM_{10}, VOC_s, CH_4$$

$$0.5 \leq \frac{E_i}{PLE_i} \leq 1 \rightarrow 0.5 \leq \frac{5M_i D_i}{W_i (PLE_i)} \leq 1$$

$$i = CO, SO_2, NO_x, CO, PM_{10}, VOC_s, CH_4$$

$$F = 5 \text{ days}, \quad W \leq 40h, \quad D \leq 8h$$

In the above equation, ER_i is exposure rate and HR_i is hazard ratio which are determined for each pollutant, separately. E_i is the extent of weekly exposure in microgram/cubic meter and PLE_i is the limit for each pollutant within the environment of workshops and factories. In order to analyze the equations, *MATLAB 2012* software and genetic algorithm optimization toolbox were used. Prior to final execution, genetic algorithm was optimized and standardized using overhead algorithm of genetic parameters. To this end, a design of experiments through response surface methodology (RSM) is carried out. For the standardization of genetic algorithm parameters, experiments are designed according to Table 3. It must be mentioned that experiments are designed using

Fig. 4 Amounts of pollutant production including SO₂, NO_x and CO during various stages of concrete production

Fig. 5 Amounts of CH₄ and VOCs pollutant produced during various stages of concrete production

Expert Design software, based on central composition design approach.

The design of experiments in $\frac{1}{2}$ fractional mode suggests a fraction of experiments with regard to 6 central points and 26 environmental points, i.e. a total of 32 experiment runs. The aforementioned genetic algorithm carries out the selection process according to roulette wheel selection method (RWS) while taking into account the selection pressure parameter. Furthermore, it must be pointed out that after assessment using the objective function, the possibility of selecting each response is calculated in Eq. 2 based on the presented pattern [30].

$$P_i = \frac{e^{-\beta r_i}}{\sum_j e^{-\beta r_j}} \quad (2)$$

$r = \text{rank}, C = \text{CostValue}, k = \text{ControlFactor}$

$\beta \geq 0$

$\beta = \text{Selection Pressure}$

for selection (β) : $\sum_{i=0}^{0.5N_{\text{Population}}} P_i \geq 0.8$

As it can be seen in Eq. 2: in this method, *beta* must be selected in a way that the total possibility of choosing the superior half of the population would be at least 80%. The conditional modality would be used as a control factor. To execute the cross-over process in this algorithm, an integration of three methods including single-point cross-over (SPX), double-point cross-over (DPX) and uniform cross-over (UX) is applied. The purpose of employing such policy is to increase the amount of exploration capability using uniform cross-over method and increasing the exploitation capability through single and double point cross-over methods. Equation 3 provides instructions on how to use such methods [31].

$$\begin{aligned} \text{Probability}(\text{SPX}) &\rightarrow \pi_{\text{SPX}} \\ \text{Probability}(\text{DPX}) &\rightarrow \pi_{\text{DPX}} \\ \text{Probability}(\text{UX}) &\rightarrow \pi_{\text{UX}} \\ \pi_{\text{SPX}} + \pi_{\text{DPX}} + \pi_{\text{UX}} &= 1 \\ \text{use : } \pi_{\text{SPX}} &= 20\% - \pi_{\text{DPX}} = 30\% - \pi_{\text{UX}} = 50\% \end{aligned} \quad (3)$$

Fig. 6 CO₂ produced during various stages of concrete production

Fig. 7 PM₁₀ emitted during various stages of concrete production

The scenario of executing genetic algorithm is done according to the strategies of Merge, Sort, and Truncation scenarios. The overall process of the scenario is illustrated in Fig. 1. The algorithm continues to the point that the end condition, i.e. number of generations resulted from analysis of overhead algorithm, is met.

Data availability The raw data and modeled results are available and authors can send them to the reviewers if they need them.

Results and discussion

Life cycle assessment (LCA) in general, is a “cradle to grave” approach for assessing industrial systems. It also is able to carry out a cross-investigation of the process which is called the “gate to gate” system. To extract the initial data, the present study assessed the concrete production sector from transportation to the plant and shipment to outside of the plant with a focus on the production of air pollutants. An overview of the life cycle in two sections of cement and concrete production is illustrated in Figs. 2 and 3, respectively.

A library review of the cited references and the analysis on LCA show that the highest cumulative concentration of a pollutant during the operation of concrete processing, i.e. 348 kg/m³-concrete belongs to CO₂ and the lowest

amount, i.e. 0.05 kg/m³-concrete belongs to VOCs. As it can be seen in Fig. 4, during the cement production stage, pollutants including SO₂, NO_x and CO would reach maximum. Furthermore, the concentration of SO₂ is increased during the concrete production stage. However, while NO_x and CO are increased during the process of internal transportation due to vehicles’ fuel consumption, their amounts would decrease in concrete production stage. Finally, they are increased once more during other internal processes within the plant as the seventh stage. Figures 5, 6 and 7 illustrate the distribution of the emission of pollutants including CH₄ and VOCs, CO₂ and PM₁₀ respectively.

As stated before, carbon dioxide gas is of special significance because a high volume of this pollutant is produced during concrete production. It is worth mentioning that in addition to creating ambrosial epidemiologic effects, the production of such gas would result in global warming. Therefore, it bears a special significance. As it can be seen in Fig. 6, the high volume emission of CO₂ gas is related to the cement production stage. In the next step, the diagram for concrete production stage also involves an uptrend. Moreover, the concentration of the pollutant (CO₂) is increased.

Figure 7 also illustrates the amount of dust particles produced with diameters less than 10 µm (PM₁₀). The results of Dose-Response studies show that there is a direct relationship between the increase of PM₁₀ and the decline of life

Table 4 Risk parameters to calculate non-linear constraints in equation analysis

Pollutant index	PM ₁₀	CO ₂	SO ₂	NO _x	VOCs	CO	CH ₄
Hazard ratio (HR)	3	2	2	2	4	3	1
Exposure rate (ER)	3	3	3	3	2	3	2
Permissible exposure limits PEL TWA	10 mg/m ³	5000 ppm	2 ppm	3 ppm	1 ppm	25 ppm	1000 ppm

Table 5 Adjustment of genetic algorithm parameters using design experiments via RSM model

Mutation rate	Cross over coefficient	Maximum iteration	Selection pressure	Initial population
0.1	0.75	250	5	50

expectancy as well as growth in mortality due to chronic diseases. It must be stated that during the initial transportation stage where the volume of fuel consumption and energy containers are increased due to travelling long distances, the volume of emitting such pollution would also increase accordingly.

Considering the regulations on pollutants' permissible exposure limits [32, 33], the time-weighted average (OEL-TWA) for carbon dioxide is 5000 ppm. This means that in the above case, the pollutant's concentration surpasses 5000 ppm during an 8-h daily working interval and weekly 40-h working time which will lead to a set of symptoms such as asphyxiation and an undesirable global warming effect. Yet, the main goal of this study is to examine the long-term effects of the production of such pollutants, because concrete processing operations are usually carried out in open environments. Hence, the pollutants would be diluted quickly and will not create acute effects. The purpose of the carried out modelling was to identify three parameters including: the extent of hourly exposure, average working hours in a week and the average time of each exposure. Genetic algorithm calculations were done to determine the aforementioned parameters with the aim of achieving an acceptable risk rate ($RR \leq 3$). Calculations of hazard ratio (HR), exposure rate (ER) and permissible limits are presented in Table 4. The results obtained from E_i/PEL_i proportion are stated as non-linear conditions and linear constraints according to the Eq. 1.

As it can be seen in Eq. 1, hazard ratio parameter remains constant within the risk function. Thus, to reduce the

environmental damages in concrete production workshops or plants, the exposure rate (ER), $E_{combine}$ factor must be decreased to minimum. However, the real conditions of workshop management involve certain limitations such as daily working hours and the aforementioned non-linear constraint stated in Eq. 2. Consequently, the calculations stated above were done through genetic algorithm. Prior to analyzing genetic algorithm, it is required to standardize the model and adjust genetic algorithm parameters by implementing the mentioned test regarding experiment design using RSM method. Using the sensitivity analysis in response surface methodology in *Expert Design* software, optimal values for genetic parameters were obtained which are shown in Table 5. Furthermore, it must be pointed out that the results derived from experiments included an acceptable outcome which is close to normal distribution. It is demonstrated in Fig. 8.

As Table 5 shows, the obtained values for the concentrations of pollutants including CH_4 , CO , $VOCs$, NO_x , SO_2 and CO_2 are as 386, 12.5, 0.65, 0.3, 0.25 and 2820 ppm, respectively. Also, PM_{10} involves a concentration of 3.5 mg/m^3 . This means that where the pollutants' concentrations were less than the above values, they would result in an acceptable risk rate (i.e. $RR \leq 3$). It is possible that the genetic algorithm takes various modes into account to obtain an optimal response. Yet, using meta-heuristic algorithms requires a physical, executive and administrative view. As a result, the obtained responses from genetic algorithm are calibrated via the present limitations and constraints in Eq. 2. However, by considering the average working hours in a week ($W = 40 \text{ h}$) as fixed in

Fig. 8 Statistical comparison of the obtained data with genetic algorithm experiments

Table 6 The desired concentration values to reach the acceptable risk rates ($RR \leq 3$) and the epidemiologic effects of each pollutant

Type of pollutant	Permissible amounts	Desired amounts for the objective function $RR \leq 3$	Epidemiologic impacts of the pollutant
CH ₄	1000 ppm	386 ppm	Severe impacts on global warming [34]
CO	25 ppm	12.5 ppm	Changes in the structures of heart and brain, changes in vision and relative transparency, neurological disorders [34, 35]
VOCs	1 ppm	0.65 ppm	Increased blood pressure and heart rate [36], developing various cancers including lung cancer [34, 35, 37]
NO _x	3 ppm	0.3 ppm	Irritated eyes, stimulation in the lower parts of the lungs, severe fatigue [34, 35]
SO ₂	2 ppm	0.25 ppm	Repertory tracts irritation, esp. in throat, nose and larynx, developing chronic bronchitis, asthma, and emphysema [34–36]
CO ₂	5000 ppm	2820 ppm	Impacts on Global warming [34]
PM ₁₀	10 mg/m ³	3.5 mg/m ³	Infections in lower and upper parts of repertory system, gastric cancer [34, 36], chronic diseases such as asthma and swelling of the nasal mucous membranes [38]

such an analysis, the average time of each exposure were calculated as 3.5 h. In other words, the safety management in a concrete production plant or workshop must substitute the staff and workers in cement processing sector in 3.5-h working intervals, making use of their services in another section. As shown in Figs. 4, 5, 6 and 7, the maximum values of emission of every pollutant occur in the cement processing stage. Subsequently, the construction workshop management must substitute the workers in this section in three 2.6-h shifts during each 8-h working interval, making use of their abilities in other units such as warehouse, transportation, loading or concrete processing. In the case studies conducted in cement production and processing sections, an average of 5, 4, and 7 people were working in *Bonyan Beton*, *Jahd Beton* and *Beton-e-Samen*, respectively. Management policies of the workshop must constantly transfer the workers in 2.6-h intervals from the area centered around cement processing to other sections of the plant or workshop. By conforming to such instructions, the epidemiologic impacts stated in Table 6 would be reduced to minimum. According to the soft computing carried out, should the manpower working in cement processing section be divided into two 4-h shifts, then the risk of developing chronic effects in the long-term are increased, as it would surpass the indicated value of 3.5 working hours. Hence, the need for creating 3 time-location shifts is made clear.

Conclusion

Due to the rapid technological advancements and various manufactured products, there is a stiff competition among various industrial and manufacturing units. The construction industry and its related subsets is an example. Meanwhile, the developing countries possess a high volume of building construction products. Given the extensive demand for building

construction products such as concrete, its life cycle assessment with focus on the production of air pollutants is studied in the present research. Moreover, a set of parameters such as the extent of hourly exposure and the desired amounts of concentrations in each pollutant will be calculated in the next step to create a desirable risk rate (i.e. $RR \leq 3$), using genetic algorithm. The results of the study limit the concentrations of hazardous pollutants such as SO₂, NO_x, CO and PM₁₀ in workshop or plant environment to 0.25 ppm, 0.3 ppm, 12.5 ppm and 3.5 mg/m³ respectively. The staff of cement processing section must undergo certain placement substitutions during each 3.5-h working time intervals so that the risks of developing diseases such as lung cancer would be reduced to minimum.

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Authors' contributions MG, MS and MM were the main investigator, collected and modeled the data, MK supervised the study. All authors read and approved the final manuscript.

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Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

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