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# Analysis of variables related to the mass flow of gaseous emissions in beehive ovens

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**Abstract.** In the combustion processes of the ceramic industry, large amounts of pollutant gas concentration are generated, so it is necessary to measure the system and the physical phenomenon, as well as the variables inherent to the process, for subsequent estimation in terms of physical magnitudes, and a dimensional analysis, this allows to generate approximations in the causal relationships of the variables. The objective of the research is to analyze the behavior of the variables involved in the process and the influence of the mass flows of polluting gases. An exploratory and experimental methodology was used, for this, the data were taken with the technique of direct measurement in the sources of gas emissions and subsequently subjected to simulation in software such as AMOS V24.0 and LISREL V8.8., on the other hand, the data were subjected to an exploratory and confirmatory factorial analysis, using SPSS software version 24.0. As a result, the variables capacity and production are practically identical, which leads to a high correlation and, consequently, an undesired multicollinearity between the variables, so the suggestion is to omit one of them. On the other hand, the sulfur percentage variable is inversely correlated with most of the variables and its saturation is not clear, so it is theoretically sustained as a latent variable of the SO2 indicator.

## 1. Introduction

The modeling of atmospheric pollution and the different elements that compose it has been worked on by several authors as reported in the literature. For the present research it is of vital importance to analyze in greater depth the modeling of air quality and the particulate matter that pollute it because of mining extraction processes, the transport of non-metallic materials or the firing processes of clay products through the different kilns [1]. Due to the great interest in the ways and means by which pollutants alter the biological balance of populations, communities and habitats, tools for impact assessment are presented, from these, the criteria, and tools for the analysis of the effects of a mining or industrial operation cause in their surrounding environment, such as health problems of organisms are exposed [2,3]. The modeling carried out with the data issued by the environmental institutions, through the air quality index, in charge of monitoring through indicators located in the cities of Bogota, Bucaramanga and Medellin, Colombia, allow calculating the emissions of respirable particulate matter (PM10) as the main air pollutant in the mining activity, as well as emissions of other pollutants such as nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$) and carbon monoxide (CO). Some studies developed a model of the dispersion of pollutants was contrasted with the quality standards in force, taking as factors the topography of the terrain, the location and the amount emitted by the sources of emission of pollutants of interest. Considering as assumptions the simultaneous operation of the equipment and the random grouping of the same, generating the probability that there are high concentrations of nitrogen dioxide (NO2) and sulfur dioxide ($SO_2$) gases on the mining blocks and in their vicinity, due to the exploitation

and transport of materials [4,5]. The models of atmospheric dispersion of pollutants, for the specific case of particulate matter, are based on the mathematical description of atmospheric processes, in which the effects such as the concentration of pollutants are generated by causes such as the evolution of particles in the air, the dynamics of the atmosphere and the emission sources. To adequately represent these phenomena, the solution of different systems of partial differential equations is required, which implies a complex mathematical problem [6-8].

In this context, given the problems that are increasingly attributed to health effects such as cardiovascular diseases and lung cancer and the environment as the deterioration of ecosystems, reduced visibility in the work area, to analyze the behavior of the particles from the time they leave the emission source, and its route in the atmosphere, mainly on large geographical environments where pollution directly or indirectly affects a population, it is had that, for the development of this research questions arose as: a) what are the variables to be analyzed in the air pollution product of the ceramic industry? b) how is the behavior and degree of relationships of these variables? c) how can these variables be mathematically represented? d) how to mathematically model the dispersion of particulate matter and other pollutants in the context of the ceramic industry? Thus, this document is structured as follows: in section 2, the methodology used for the development of the research is presented; in section 3, answers are given to the questions mentioned above, addressing the mathematical correlation of the variables, presenting an exploratory and confirmatory analysis, and determining the relationship between the variables under study; finally, in section 4, conclusions and a final contribution are presented.

## 2. Methodology

The review of the reports and instruments applied generated data to be analyzed, so that finally there were fourteen (14) variables, all a continuous quantitative nature. Consequently, a descriptive analysis was performed, based on summary measures for all the variables of interest, this procedure was done for both the original sample and the simulated sample [9,10]. The analysis of the reports with the support of technical and specialized personnel allowed the configuration of the database, considered as the original sample, with the analysis of reports on beehive furnaces, and which generated 14 variables of continuous quantitative nature, whose nomenclature for the analysis of the data and formulation of the model is summarized in the Table 1.

**Table 1.** Nomenclature of the variables involved in the analysis.

|  | Variable | Nomenclature |
|---|---|---|
| 1 | Capacity (TON/quema) | Capa |
| 2 | Production during measurement (TON) | Produc |
| 3 | Particulate matter concentration (mg/m$^3$) | Mp |
| 4 | % Moisture content in chimney | Porcon |
| 5 | Actual fuel consumption (TON/quema) | Consum |
| 6 | Concentration SO$_2$ (mg/m$^3$) | So2 |
| 7 | Absolute stack pressure (mmHg) | Pressure |
| 8 | Stack gas velocity (m/s) | Veloci |
| 9 | Calorific value of fuel (BTU) | Power |
| 10 | Chimney diameter (m) | Diamet |
| 11 | Chimney temperature (ºC) | Temper |
| 12 | Chimney height (m) | Height |
| 13 | Concentration NOx (mg/m$^3$) | Nox |
| 14 | % Sulfur in fuel | Porazu |

From the latent variable approach, we initially proceeded to perform an exploratory factor analysis (EFA), based on the following steps: 1) determination of the correlation matrix; 2) verification of application assumptions; 3) extraction of factors. 4) denomination and interpretation of the factors.

This procedure was carried out using SPSS software version 24.0. The AFE provides the factorial structure to be assessed in the confirmatory factor analysis (CFA) through the application of structural

equation models (SEM). In this phase, programs were run in several software, mainly AMOS Version 24.0 and LISREL Version 8.81. The general procedure followed is summarized in the following steps: 1) specification of the input model. 2) evaluation of the model identification. 3) parameter estimation. 4) model fitting. 5) re - specification of the model. As a result of this phase, we obtain the configuration of the measurement model and the structural model that form the basis for the formulation and testing for the definition of a predictive model [11,12].

## 3. Results and discussion

First, a descriptive analysis of the data from the original sample and the simulated sample is made, the descriptive statistics are presented, and the descriptive values are compared for the variables related to the pollutants, *i.e.*: particulate matter (PM), sulfur dioxide ($SO_2$) and nitrogen oxides (NOx). Secondly, an approach from latent variable models using structural equations to an integral model that addresses the three pollutant concentration variables, from observation with other related variables, is shown.

### 3.1. Descriptive analysis

The average capacity of the kilns is 96.35 tons (TON), with a high standard deviation of 25.79 TON. Fifty percent of the kilns have an approximate capacity between 83 TON and 100 TON. The kilns produce at maximum capacity; consequently, capacity and production share the same values. The average moisture content percentage is 4.74% with a high standard deviation (SD) that reaches 2.72%. Fifty percent of the kilns have a moisture content percentage ranging from 2.93% to 5.65%. The average actual fuel consumption is 11.54 TON and more than 50% of the kilns consume more than 12 TON of fuel.

As reported in Table 2, in reference to the absolute stack pressure, its average value in the original sample is 736.81 mmHg, while the average gas velocity in the stack is 4.11 m/s, however, 50% of the furnaces reach velocities between 3.73 m/s and 4.57 m/s. On the other hand, the average calorific value of the fuel is 13 655 BTU and its values range between 13 190 BTU and 13 820 BTU, managing a range of approximately 600 BTU in the original set. The percentage of sulfur in the fuel is less than 1%, with an average value of 0.96% and a minimum value of 0.02%. On the other hand, the average diameter of the chimney is 1.32 m, and the average height is 15.24 m., the heights of the chimneys range between 13 m and 17.5 m, while the maximum temperature recorded is 217.85 °C and an average value of 106.28 ° C. The simulated values related for the simulated sample are like those of the original sample, so we can deduce that they are similar.

The statistics of the concentration of PM, $SO_2$ and $NO_x$ pollutants in the original and simulated samples are reported in Table 3, where the mean concentration of PM in the original sample is 84.31 mg/m$^3$, while in the simulated sample this value rises slightly to 101.74 mg/m$^3$. The range of PM concentration in the original sample oscillates approximately between 10 mg/m$^3$ and 180 mg/m$^3$, in reference to $SO_2$ the average concentration is 18.95 mg/m$^3$ and in the simulated sample it is 21.51 mg/m$^3$. Fifty percent of the furnaces in the simulated sample have a $SO_2$ concentration higher than 19.17 mg/m$^3$. The average $NO_x$ concentration in the original sample is 62.02 mg/m$^3$ and in the simulated sample it increases slightly to 65.62 mg/m$^3$, the maximum $NO_x$ value in the original sample is 235.57 mg/m$^3$, while in the simulated sample it increases significantly to 523.39 mg/m$^3$.

### 3.2. Approach from latent variable models

A first approach to a model of the concentration of pollutants in furnaces is based on latent variable models, *i.e.*, considering the concentrations of PM, $SO_2$ and $NO_x$ as variables that are explained by other continuous observed variables. This approach will allow, on the one hand, to assess the structural model, that is, the levels of correlation or covariation between these latent variables and, on the other hand, to obtain the estimated parameters for an overall assessment of the pollutant concentration potential of the beehive kilns of the study.

The input model is reflected in Figure 1, where the theoretical configuration is derived from the literature review, which suggests a three-dimensional construct formed by the latent variables: PM, $SO_2$

and NOx and the observed variables:capacity (Capa), production, (Produc), percentage of moisture content (Porcon), actual fuel consumption (Consum), Absolute stack pressure (Pressure), stack gas velocity (Veloci), calorific value of fuel (Power),percentage of fuel sulfur (PorAzu), diameter (Diamet), Height (Height) and stack temperature (Temper).

**Table 2.** Descriptive statistics of the original and simulated samples.

|  | Mean | Standard deviation | Median | Maximum | Minimum | Percentile 25 | Percentile 75 |
|---|---|---|---|---|---|---|---|
| | | | Original sample | | | | |
| Capa | 96.35 | 25.90 | 91.50 | 154.00 | 68.40 | 82.70 | 100.00 |
| Produc | 96.43 | 25.85 | 91.50 | 154.00 | 68.40 | 83.00 | 100.00 |
| PorCon | 4.74 | 2.12 | 4.80 | 8.87 | 2.31 | 2.93 | 5.65 |
| Consum | 11.54 | 3.02 | 12.00 | 17.90 | 8.80 | 8.80 | 12.00 |
| Pressure | 736.81 | 6.89 | 740.12 | 740.86 | 721.61 | 735.74 | 740.15 |
| Veloci | 4.11 | 0.65 | 4.06 | 5.10 | 3.05 | 3.73 | 4.57 |
| Power | 13655.00 | 287.15 | 13800.00 | 13820.00 | 13190.00 | 13495.00 | 13820.00 |
| PorAzu | 0.96 | 0.02 | 0.96 | 0.99 | 0.94 | 0.94 | 0.97 |
| Diamet | 1.32 | 0.21 | 1.28 | 1.70 | 1.10 | 1.17 | 1.44 |
| Height | 15.24 | 1.31 | 15.00 | 17.50 | 13.00 | 14.95 | 15.75 |
| Temper | 106.28 | 59.83 | 88.65 | 217.85 | 38.50 | 67.53 | 140.75 |
| | | | Simulated sample | | | | |
| Capa | 97.93 | 19.40 | 95.08 | 151.72 | 68.52 | 81.87 | 112.05 |
| Produc | 97.86 | 19.33 | 95.31 | 152.03 | 68.64 | 81.96 | 111.25 |
| PorCon | 5.74 | 1.75 | 5.78 | 8.84 | 2.85 | 4.24 | 7.23 |
| Consum | 12.00 | 2.09 | 11.79 | 17.51 | 8.87 | 10.26 | 13.47 |
| Pressure | 735.50 | 6.75 | 735.11 | 757.22 | 713.32 | 730.87 | 740.47 |
| Veloci | 4.04 | 0.59 | 4.03 | 5.10 | 3.05 | 3.52 | 4.55 |
| Power | 13602.54 | 140.81 | 13620.49 | 13812.89 | 13227.16 | 13491.96 | 13723.70 |
| PorAzu | 0.96 | 0.01 | 0.96 | 0.99 | 0.94 | 0.95 | 0.98 |
| Diamet | 1.40 | 0.18 | 1.41 | 1.70 | 1.10 | 1.25 | 1.56 |
| Height | 15.53 | 1.27 | 15.71 | 18.41 | 11.14 | 14.82 | 16.47 |
| Temper | 139.13 | 47.08 | 139.75 | 217.73 | 56.46 | 98.02 | 179.16 |

**Table 3.** Descriptive statistics contaminating original and simulated sample.

| | | | Original sample | | | | |
|---|---|---|---|---|---|---|---|
| | Mean | Standard deviation | Median | Maximum | Minimum | Percentile 25 | Percentile 75 |
| MP | 84.31 | 55.23 | 95.96 | 179.46 | 9.90 | 38.72 | 107.89 |
| $SO_2$ | 18.95 | 17.28 | 15.62 | 55.68 | 1.02 | 6.96 | 24.88 |
| NOx | 62.02 | 72.28 | 36.03 | 235.57 | 11.75 | 26.38 | 62.00 |
| | | | Simulated sample | | | | |
| MP | 101.74 | 34.47 | 104.92 | 177.98 | 16.51 | 79.57 | 124.95 |
| $SO_2$ | 21.51 | 12.32 | 19.17 | 55.58 | 1.82 | 11.01 | 30.78 |
| NOx | 65.62 | 73.75 | 41.80 | 523.39 | 3.11 | 21.39 | 77.03 |

*3.3. Confirmatory phase*

The input model of Figure 2., is subjected to an exploratory factor analysis through the simulated sample, in which the correlations between the variables, their sampling adequacy and factorial configuration are analysed. Subsequently, this factorial structure will be subjected to verification by means of a confirmatory model. For this purpose, the Pearson correlation matrix was performed for the variables of the set, the range of variation of the correlation coefficients is wide and oscillates approximately between - 0.64 and 0.98 ($-0.64 \leq r \leq 0.98$). The PorAzu variable shows generally moderate inverse correlations with most of the variables in the set, while the Diamet variable shows lower correlations.

In reference to the evaluation of the basic assumptions of application (KMO = 0.70, value of the determinant = 0.005 and Barlett's test of sphericity, p = 0.00) indicate that the assumptions of application of the factorial model are fulfilled, ratifying the adequacy of this technique.) The structure matrix is

made with the observed variables and their saturation in each of the factors, it is observed that all the variables, except for the percentage of sulfur in the fuel (PorAzu) clearly saturate in each of the proposed factors. Since PorAzu is a variable that can be theoretically related to $SO_2$ and $NO_x$, and based on Figure 3, graph of components rotated in space, we consider the variable PorAzu as an indicator for the $SO_2$ solution.
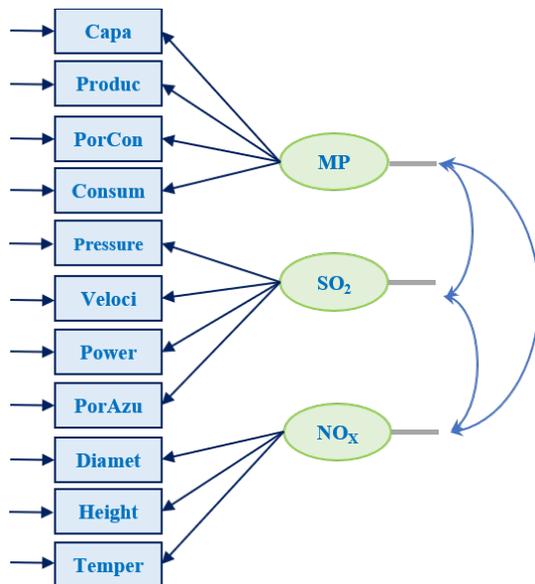


**Figure 1.** Contaminant concentration input model.



Chi – Square = 2871.11, df = 32,
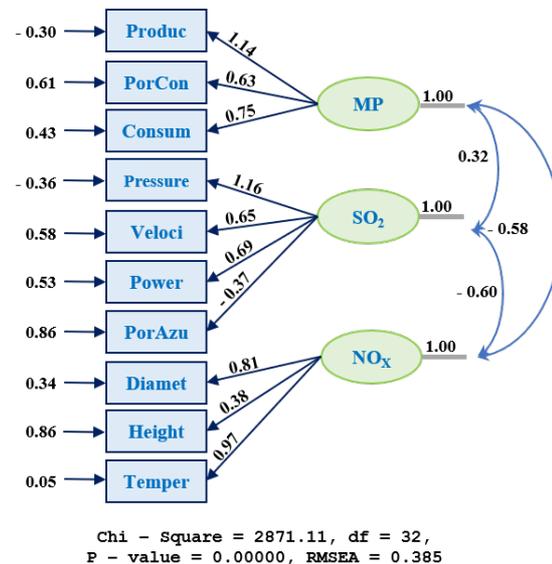P – value = 0.00000, RMSEA = 0.385

**Figure 2.** Standardized solution and fit indices for the specified model.

Figure 4 shows the reformulated model after the change from covariances to correlations of the variables: PM, $SO_2$ and $NO_x$. The standardized solution is shown in Figure 5, where we can see that the value of the relative chi-square ($\chi^2$/df) is greater than 50 and the parsimony of the model improved significantly, as revealed by the root mean square error of approximation (RMSEA) with a value of 0.19, although these values are not completely optimal, they reflect a considerable improvement with respect to the specified model. The standardized loadings present t-statistics with values greater than ±1.96, indicating that they are significantly different from zero in the population with a significance level α = 0.05. Error estimates are generally acceptable and range from 0.04 to 0.56.

The squared multiple correlation coefficients (R2) of the indicators, which indicate the proportion of variance explained by the construct, *i.e.*, the intensity of the relationship specified in the model between each indicator and the construct to which it belongs reaches varied values ranging between 0.12 and 0.93.

From the latent variable models (LVM) approach, the following conclusions can be drawn, which will serve as a basis for the formulation of the predictive model in the next phase of the analysis: 1) the approximation by MEE evidences a conceptual construction in the framework of the structural model and the measurement model, however, although it is possible to reach a solution to the proposed model the same is not totally adjusted, this suggests that the measurement of the main pollutants PM, $SO_2$ and $NO_x$, can be considered as an observed variable instead of a latent variable; 2) the analysis by means of SEM suggests a proven relationship between the structural model, that is, the quantity or measurement of PM is considered to be an independent variable from which the behavior of $SO_2$ and $NO_x$ can be explained; and 3) the solution obtained from the SEM allowed validating the indicators associated to each type of pollutant, despite sharing common aspects and elements in the measurement framework, it was possible to define the appropriate saturation of each indicator (for example, the percentage of sulfur), which will undoubtedly facilitate the formulation of a predictive model based on the analysis of the observed variables.
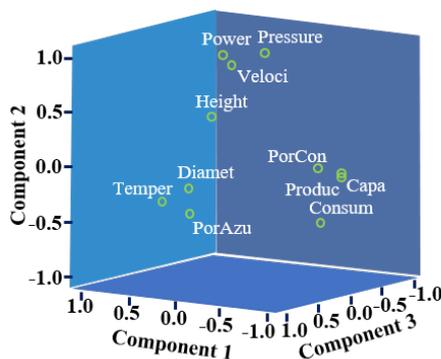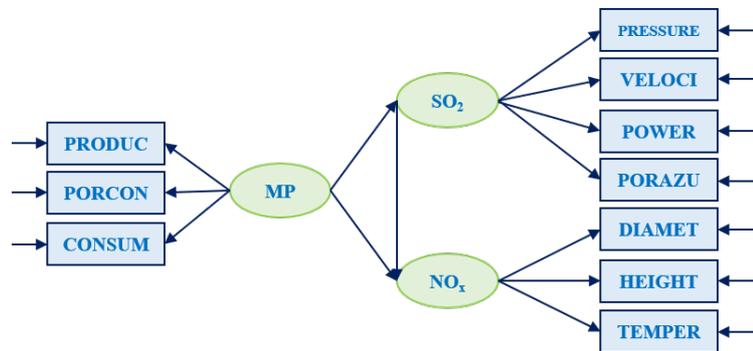
**Figure 3.** Three-factor solution rotated component plot.



**Figure 4.** Respecified model.



Chi − Square = 1645.14, df = 32,
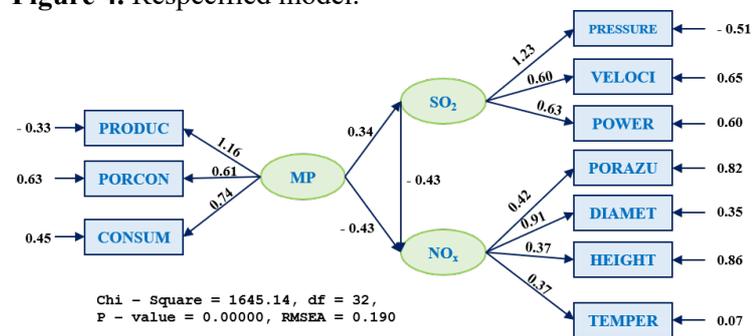P − value = 0.00000, RMSEA = 0.190

**Figure 5.** Respecified model; standardized solution.

## 4. Conclusions

These emission determination tests are called technical reports of emission monitoring in fixed sources or colloquially called by businessmen as isokinetic studies and with them it is possible to measure the particulate matter through isokinetic sampling in fixed sources. This determination of a fixed emission source (chimneys, ovens, among others) is carried out to establish the mass flow of pollutant from the concentration of the same and the flow of the gas that transports it, being the sample taken directly from the emission source using rigorously the methods defined by the environmental authorities. The importance of this type of studies lies in the identification of the sources of atmospheric pollution with concentration values and their variables, to initiate actions aimed at mitigating or eliminating the pollutant to carry out environmentally friendly processes.

When developing the model specified in the exploratory phase, some anomalous situations were found, such as; the capacity and production variables are practically identical which leads to a high correlation and consequently and undesired multicollinearity between the variables, so the production variable is considered instead of the capacity variable and the production capacity is excluded from this model since in all the kilns the maximum capacity is produced overlapping these two variables; the second situation is that the variable percentage of sulfur (PorAzu) is inversely correlated with most of the variables and its saturation is not clear, so it is theoretically sustained as a latent variable of the $SO_2$ indicator.

From the latent variable models' approach, the structural equation models approach shows a conceptual construction within the framework of the structural model and the measurement model; however, although a solution to the proposed model is achieved, it is not fully adjusted, which suggests that the measurement of the main pollutants PM, $SO_2$ and NOx can be considered as an observed variable instead of a latent variable.

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