

A Generalized Approach to Understand the CoMFA and CoMSIA Analysis Within the Framework of Density Functional Theory

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Abstract: Our working group has worked to find methodologies that can relate the CoMFA and CoMSIA calculations with density functional theory, considering the mathematical context that it represents in terms of chemical reactivity indices. Currently, the three-dimensional quantitative structure-activity relationship (3D QSAR) models have many applications; however due to the complexity to understand its results is necessary postulate new methodologies. In this sense, this work postulates a generalized version joining the quantum similarity field and chemical reactivity descriptors within the framework of density functional theory. One of the advantages of Quantum Molecular Similarity is that it uses electronic density as object of study. The CoMFA and CoMSIA results can be modeled joining MQS and chemical reactivity; in this context these outcomes can be applied in QSAR correlations and docking studies to understand the biological activity of some molecular set. This generalized methodology can be applied to understand the biological activity on a molecular set taking a reference compound. In order to understand its corrections from the structural and electronic point of view.

Keywords: CoMFA, CoMSIA, 3D-QSAR, Molecular Quantum Similarity (MQS), Chemical Reactivity Descriptors, Density Functional Theory (DFT)

1. Introduction

In two recent publications our researcher group shown as the Comparative Molecular Field Analysis (CoMFA) and the Comparative Molecular Similarity Indexes Analysis (CoMSIA) can be understood in terms of Molecular Quantum Similarity (MQS) and Density Functional Theory (DFT)-based reactivity descriptors [1-8]. Taking into account that the CoMFA and CoMSIA analysis have many applications in the three-dimensional Quantitative Structure-Activity Relationships (3D QSAR) studies, in this work are presented a new considerations about these methodologies into the DFT context.

In the DFT framework, the MQS is a field very applied, was introduced by Carbó and co-workers [2-6]. In the MQS field the key variable is the density function [9-11]; therefore it reasonable think that can be related with the chemical reactivity descriptors such as chemical hardness (η), softness (S),

electrophilicity (ω) and Fukui Functions. Therefore, employing this hybrid methodology (joining the MQS and chemical reactivity) we hope show new insight on the understanding of the CoMFA and CoMSIA results within the DFT context. In this form, the main aim of this work is presents new relationship between the MQS and Chemical reactivity that can be applied on the CoMFA and CoMSIA analysis.

2. Theoretical Details

2.1. Quantum Object Sets (QOS)

Considering the follow set: $Z = \{z_I | I = 1, N\}$, being N the set cardinality, is the Cartesian product of two sets: $Z = \{P \times M\}$, where $P = \{p_I | I = 1, N\}$ is the set of the objects and $M = \{m_I | I = 1, N\}$ the set of tags. Therefore, we can write:

$\forall I=1, N: z_I = (p_I; m_I) \in Z$ [12-16]. In this sense, a (QOS) is a tagged set: $Q = P \times S$ made by a set of submicroscopic objects and a set of quantum mechanical Density Function (DF): $S = \{\rho_I | I=1, N\}$, as elements of the tag set.

Of this form, we can use the Hilbert semispace tag set S and define a central averaged DF using the expression:

$$\rho_C = N^{-1} \sum_I \rho_I \rightarrow \langle \rho_C \rangle = N^{-1} \sum_I \langle \rho_I \rangle = N^{-1} \sum_I v_I = v_C \quad (1)$$

$$S = \{\rho_I | I=1, N\} \rightarrow \forall \langle \rho_I \rangle = v_I \wedge \sigma_I = v_I^{-1} \rho_I \wedge \langle \sigma_I \rangle = 1 \rightarrow H = \{\sigma_I | I=1, N\} \quad (3)$$

From this equation (3), we can write the shape centroid function as:

$$\sigma_C = N^{-1} \sum_I \sigma_I \rightarrow \langle \sigma_C \rangle = N^{-1} \sum_I \langle \sigma_I \rangle = N^{-1} N = 1 \quad (4)$$

2.2. Local Molecular Quantum Similarity Measure: A Generalized Version

The quantum similarity measure Z_{AB} between compounds A and B, with electron density $\rho_A(r_1)$ and $\rho_B(r_2)$ respectively, can be understood using the minimizing of the expression for the Euclidean distance as [12-15]:

$$\begin{aligned} D_{AB} &= \left(\int |\rho_A(r) - \rho_B(r)|^2 dr \right)^{1/2} \\ &= \left(\int (\rho_A(r_1))^2 dr_1 + \int (\rho_B(r_2))^2 dr_2 - 2 \int \rho_A(r_1) \rho_B(r_2) dr_1 dr_2 \right)^{1/2} \\ &= \sqrt{Z_{AA} + Z_{BB} - 2Z_{AB}} \end{aligned} \quad (5)$$

Where Z_{AB} is the overlap integral between the electron density of the compound A and B into the (QOS), Z_{AA} and Z_{BB} are the self-similarity of compounds A and B [16].

In this researcher we have used the Carbó index due to that is very used in the quantum similarity context [12-15]:

$$I_{AB} = \frac{\int \int \rho_A(r_1) \rho_B(r_2) dr_1 dr_2}{\sqrt{\left(\int \rho_A(r_1) dr_1 \right)^2 \left(\int \rho_B(r_2) dr_2 \right)^2}} \quad (6)$$

As the main structural difference on the molecules used by our group in the previous work are local differences [1]; the similarity features can be associated from the local point of view, in this order of ideas is used the Hirshfeld approach to study the local quantum similarity.

With the aim to obtain a generalized Hirshfeld approach to our systems, considering the electron density $\rho(r)$ in contribution $\rho_{x^1}(r)$, where x^1 is an atom. These contributions allow define a concept of atom in a reference system and study its (dis)similarity on a molecular set (i.e.; substituent effect analysis). On the other hand, these contributions are proportional to the weight $w_C(r)$ of the electron density of the isolated compound in the so-called *promolecular density* [17-20]. The promolecular density is defined as:

$$\rho_{x^1}^{Prom}(r) = \sum_y \rho_y^0(r) \quad (7)$$

with the DF Minkowski norms being define as:

$$\forall I=1, N: \langle \rho_I \rangle = \int_D \rho_I(r) dr = v_I \quad (2)$$

Therefore, the centroid DF can be seen as a function describing the arithmetic average of the number of particles v_C of all quantum objects involved. To relate the shape functions associated to the quantum set, we define tag set H associated to the DF set S , therefore we have:

To calculate the contribution of an atom (x) in the electron density in a molecule A $\rho_A(r)$ we have:

$$\rho_{x^1}(r) = w_{x^1}(r) \rho_A(r) \quad (8)$$

In this form, the weight ($w_x(r)$) is obtained as:

$$w_{x^1}(r) = \frac{\rho_{x^1}^0(r)}{\sum_y \rho_y^0(r)} \quad (9)$$

Here $\rho_{x^1}^0(r)$ is the electron density of the isolated carbon atom x^1 , (i.e.; the reference electron density) [21]. In this sense, the contribution atomic of other carbon atom (x^2) in a molecule B is obtained as:

$$\rho_{x^2,B}(r) = w_{x^2}(r) \rho_B(r) \quad (10)$$

with

$$w_{x^2,B} = \frac{\rho_{x^2,B}^0(r)}{\sum_y \rho_y^0(r)} \quad (11)$$

So we can write the contribution of the asymmetric carbon atom products $\rho_A(r) \rho_B(r)$ as:

$$\rho_{x,AB}(r) = w_{x,AB}(r)\rho_A(r)\rho_B(r) \quad (12)$$

Using the equations (7-12) we can write the numerator Z_{AB} in the Carbó index (equation (6)) as:

$$\begin{aligned} Z_{A,B}^{Local,x} &= \frac{Z_{AB}}{\sqrt{Z_{AA}Z_{BB}}} \\ &= \frac{\iint w_{x,AB}\rho_A(r)\rho_B(r)dr_Adr_B}{\sqrt{\left(\int w_{x,A}(r)\rho_A(r)dr_A\right)^2 \left(\int w_{x,B}(r)\rho_B(r)dr_B\right)^2}} \end{aligned} \quad (13)$$

The equation (10) is a generalized Hirshfeld approach to our systems [1], where x is an atom, therefore we can write the global index (equation (6)) as local contributions. In this context, is possible study the local similarity and the substituent effects on some reference compound into the (QOS).

2.3. Reactivity Descriptors

The CoMFA and CoMSIA analysis are understand in terms of physical-chemistry properties such as electrostatic, hydrophobic and hydrogen-bond donor or acceptor properties, these properties can be related with global chemical descriptors as chemical potential, hardness, electrophilicity index and local reactivity descriptors as the Fukui Functions. In the DFT context, the global reactivity indexes give information about the reactivity or stability of a chemical system front to external perturbations.

The chemical potential (μ) can be understood as the tendency that have the electrons to exit of the electron cloud and is calculate according to the equation:

$$\mu \approx \frac{\varepsilon_H + \varepsilon_L}{2} \quad (14)$$

Where (ε_H) is the energy of the (HOMO) and (ε_L) is the energy of the (LUMO) [22, 23]. Using the equation (14) the chemical hardness is defined according to Pearson et. al. [24].

$$\eta \approx \varepsilon_L - \varepsilon_H \quad (15)$$

From the equation (12), we obtain the softness [25] as:

$$S = \frac{1}{\eta} \quad (16)$$

Finally, using the equations (14) and (15) is defined the electrophilicity index (ω) [25, 26]. This index is understood as the measure of the stabilization energy of the system when it is saturated by electrons from the external environment and is calculated as follows:

$$\omega = \frac{\mu^2}{2\eta} \quad (17)$$

Finally, the Fukui Functions (equations (18) and (19), $f(r)$) are defined as the derivative of the electronic density

with respect to the number of electrons at constant external potential:

$$f_k^+ \approx \int_k [\rho_{N+1}(\vec{r}) - \rho_N(\vec{r})] = [q_k(N+1) - q_k(N)] \quad (18)$$

$$f_k^- \approx \int_k [\rho_N(\vec{r}) - \rho_{N-1}(\vec{r})] = [q_k(N) - q_k(N-1)] \quad (19)$$

Where q_k refers to the electron population at k^{th} atomic site in a molecule. (f_k^+) governing the susceptibility for nucleophilic attack and (f_k^-) governing the susceptibility for electrophilic attack [27-30].

2.4. Quantum Operators to Calculate Local Similarity

One the most operator used in quantum similarity is the Dirac delta distribution $\Omega(r_1, r_2) = \delta(r_1, r_2)$ [31] so called overlap molecular quantum similarity measure and relates the volume associated with the overlap of the two densities $\rho_A(r)$ and $\rho_B(r)$:

$$\begin{aligned} Z_{A,B}^{Local,x}(\Omega) &= \frac{Z_{AB}(\Omega)}{\sqrt{Z_{AA}(\Omega)Z_{BB}(\Omega)}} \\ &= \frac{\iint w_{x,AB}\rho_A(r)\delta(r_1 - r_2)\rho_B(r)dr_Adr_B}{\sqrt{\left(\int w_{x,A}(r)\rho_A(r)dr_A\right)^2 \left(\int w_{x,B}(r)\rho_B(r)dr_B\right)^2}} \quad (20) \\ &= \frac{\iint w_{x,AB}\rho_A(r)\rho_B(r)dr_Adr_B}{\sqrt{\left(\int w_{x,A}(r)\rho_A(r)dr_A\right)^2 \left(\int w_{x,B}(r)\rho_B(r)dr_B\right)^2}} \end{aligned}$$

Using this equation 20, is possible obtain information about the electron concentration in the molecule and indicates the degree of overlap between the compared compounds.

Another operator very used in quantum chemistry is the Coulomb operator $\Phi(r_1, r_2)$, defined as $\Phi(r_1, r_2) = |r_1 - r_2|^{-1}$, this operator represents the electronic coulomb repulsion energy between molecular densities $\rho_A(r)$ and $\rho_B(r)$ as:

$$\begin{aligned} Z_{A,B}^{Local,x}(\Phi) &= \frac{Z_{AB}(\Phi)}{\sqrt{Z_{AA}(\Phi)Z_{BB}(\Phi)}} \\ &= \frac{\iint w_{x,AB}\rho_A(r)\left(1/|r_1 - r_2|\right)\rho_B(r)dr_Adr_B}{\sqrt{\left(\int w_{x,A}(r)\rho_A(r)dr_A\right)^2 \left(\int w_{x,B}(r)\rho_B(r)dr_B\right)^2}} \quad (21) \\ &= \frac{\iint w_{x,AB}\rho_A(r)\rho_B(r)dr_Adr_B}{\sqrt{\left(\int w_{x,A}(r)\rho_A(r)dr_A\right)^2 \left(\int w_{x,B}(r)\rho_B(r)dr_B\right)^2}} \end{aligned}$$

The Carbó index is restricted to the range (0,1) where $C_{AB}=0$ means dis(similarity) and $C_{AB}=1$ self-similarity, according to the Schwartz integral.

$$\left[\int \rho_A(r) \rho_B(r) dr \right]^2 \leq \int \rho_A^2(r) dr \int \rho_B^2(r) dr \quad (22)$$

2.5. Quantum Similarity Matrix

The quantum similarity Matrix can be associated to a $[N \times N]$ metric associated to a (QOS) tag set made of quantum mechanical density function $S = \{\rho_I | I = 1, N\}$ as:

$$Z = \begin{bmatrix} \langle z_1 | \\ \langle z_2 | \\ \vdots \\ \langle z_N | \end{bmatrix} = [\langle z_1 | \langle z_2 | \cdots \langle z_N |] \quad (23)$$

In the equation (23) there are equivalence between rows and columns. In this sense, we have:

$$\begin{aligned} Z &= \{Z_{IJ} = \langle \rho_I | \rho_J \rangle | I, J = 1, N\} \\ \wedge |z_I\rangle &= \{Z_{JI} | J = 1, N\} \\ \wedge \langle z_I| &= \{Z_{IJ} | J = 1, N\} \end{aligned} \quad (24)$$

Another property important of the matrix Z is its symmetry, according to:

$$Z = Z^T \rightarrow \forall I, J : Z_{IJ} = Z_{JI} \quad (25)$$

Taking in account these properties associated to the similarity matrix, we can express the local molecular similarity measures using the overlap and coulomb operators (equations (20) and (21)).

2.6. Joining QS and Chemical Reactivity

According to Carbó et al. [32] it is possible to consider a set of specific vectors and to associate a center for this QOS. Therefore a QOS represented by Fukui Functions can be defined as:

$$M = \{|I\rangle | I = 1, N\} \quad (26)$$

In eq. 23, the first order densities can be constructed by a set of molecular orbital (MO) of shape functions contributions as:

$$P = \{\sigma_I = |I\rangle \langle I| | I = 1, N\} \quad (27)$$

The P elements correspond to the squared MO modulus. Using these consideration we can relate the frontier orbital (HOMO and LUMO) on the QOS. Defining $\{w_I\}$ as the number of occupations in the MOs, we can construct a linear combination of P to the first order density functional as [33]:

$$\rho = \sum_I w_I \sigma_I \quad (28)$$

with

- i. ν is the number of electrons: $\sum_I w_I = \nu$
- ii. where the Minkowski norms of the elements of the shape function set P are normalized to unity, belonging to the MO set normalization ($\forall I : \langle \sigma_I | = 1$).

Therefore we can define a centroid shape function using an average function.

$$\sigma_C = N^{-1} \sum_I \sigma_I \rightarrow \langle \sigma_C \rangle = 1 \quad (29)$$

In this sense, each elements of set P can be compared with the centroid function and can be built as:

$$\forall I : \theta_I = \sigma_I - \sigma_C \rightarrow Z = \{\theta_I | I = 1, N\} \quad (30)$$

Finally the Minkowski pseudonorm of the centroid shape function set Z can be written as:

$$\forall I : \theta_I = \langle \sigma_I - \sigma_C \rangle = \langle \sigma_I \rangle - \langle \sigma_C \rangle = 0 \quad (31)$$

Therefore the shifted elements have a null Minkowski pseudonorm. Where the shape function is comprised of N linearly independent elements. Using these relations we can make quantum similarity using the Fukui Functions on the QOS taking in account a reference compound.

$$Z_{AB}(f^{+/-}(r)) = \frac{[f^{+/-}(r)]_A [f^{+/-}(r)]_B}{\sqrt{[f^{+/-}(r)]_A^2 [f^{+/-}(r)]_B^2}} \quad (32)$$

Using the equation (32), we can built scales of convergence quantitative see reference 1, among other. This equation shows a possible join between quantum similarity and chemical reactivity and can be used to calculate the quantum similarity on the local chemical reactivity (Fukui functions).

3. Conclusions

In this work are reported new insights about the relationship between quantum similarity and chemical reactivity in a generalized form. This hybrid methodology, allow us study the steric and electrostatic effects in form of the scales of convergence quantitative; substituent effects among others (see reference 1).

In this sense, the CoMFA and CoMSIA results can be modeled joining MQS and chemical reactivity; in this context these outcomes can be applied in QSAR correlations and docking studies to understand the biological activity of some molecular set. Taking into account that this methodologies can be used when the receptor is known or even when it is not known.

Conflict of Interest

The authors declare no conflict of interest.

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