Organic &
Biomolecular
Chemistry

Cite this: *Org. Biomol. Chem.*, 2012, **10**, 2855

www.rsc.org/obc

PAPER

# Understanding local electrophilicity/nucleophilicity activation through a single reactivity difference index

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***Received 18th November 2011, Accepted 7th February 2012***
**DOI: 10.1039/c2ob06943a**

A local reactivity difference index $R_k$ is shown to be able to predict the local electrophilic and/or nucleophilic activation within an organic molecule. Together with the electrophilic and/or nucleophilic behavior of the center k given by the sign, the magnitude of the $R_k$ index accounts for the extent of the electronic activation, a behavior that allows for the use of the $R_k$ index as a measure of the molecular reactivity especially in polar processes.

## Introduction

Based on the electronic behavior of breaking and forming bonds, an organic reaction can be classified as a non-polar or a polar reaction. While non-polar reactions involve species with some radical character, polar reactions take place through zwitterionic species. Most organic molecules having polarized functional groups present polar reactivity, which is characterized by nucleophilic–electrophilic interactions. An electrophile is a neutral or positively charged molecule able to accept an amount of electron density along a polar reaction, whereas a nucleophile is a neutral or negatively charged molecule able to donate an amount of electron density during the reaction. Thus, during a polar reaction electrophiles and nucleophiles form new bonds *via* electron transfer from the nucleophiles to the electrophiles.[1–3] The chemistry of electrophiles and nucleophiles is intimately connected to that of Lewis acids and bases as well as of redox partners. There are certain ambiphilic reagents which may, however, simultaneously act as both electrophiles and nucleophiles.

Parr and coworkers[4] have introduced the following definition of electrophilicity ($\omega$) within a conceptual density functional theory (DFT) framework,[5] by taking a cue from the work of Maynard and coworkers,[6]

$$\omega = \mu^2/2\eta = \chi^2/2\eta \tag{1}$$

where the chemical potential ($\mu$), the negative of the electronegativity ($\chi$), is the derivative of the total energy with respect to the electron number $N$ at a constant external potential $\upsilon(\mathbf{r})$, and is given by[7]

$$\mu = -\chi = \left(\frac{\partial E}{\partial N}\right)_{\upsilon(\mathbf{r})} \approx -\frac{I+A}{2} \approx \frac{E_{\mathrm{HOMO}} + E_{\mathrm{LUMO}}}{2} \tag{2}$$

where $I$ and $A$ are the ionization potential and the electron affinity, and $E_{\mathrm{HOMO}}$ and $E_{\mathrm{LUMO}}$ are the frontier molecular orbital energies, respectively.

Hardness ($\eta$) is the corresponding second derivative defined as follows[8]

$$\eta = (\partial^2 E/\partial N^2)_{\upsilon(\mathbf{r})} \approx I - A \approx E_{\mathrm{LUMO}} - E_{\mathrm{HOMO}} \tag{3}$$

Since, the process of donating electron density from a neutral molecule is thermodynamically unfavorable, better nucleophiles can be considered to be those having a low ionization potential. Based on this idea, Domingo *et al.* have introduced an empirical (relative) nucleophilicity index ($N$) based on the HOMO energies obtained within the Kohn–Sham scheme,[9] and defined as[10]

$$N = E_{\mathrm{HOMO(Nu)}}\ (\mathrm{eV}) - E_{\mathrm{HOMO(TCE)}}\ (\mathrm{eV}) \tag{4}$$

Nucleophilicity is defined relative to tetracyanoethylene (TCE) because it presents the lowest HOMO energy in a large series of molecules already investigated in the context of polar cycloadditions. This choice allows us to conveniently handle a nucleophilicity scale of positive values.

Local electrophilicity[11] ($\omega_k$) and local nucleophilicity[12] ($N_k$), at the atomic site k may be defined in terms of the related condensed Fukui functions, $f_k^{\,+}$ and $f_k^{\,-}$, as

$$\omega_k = \omega . f_k^{\,+} \tag{5a}$$

and

$$N_k = N . f_k^{\,-} \tag{5b}$$

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where the Fukui functions condensed at the atomic site k, for the nucleophilic attack ($f_k^+$) and for the electrophilic attack ($f_k^-$) may be written in terms of the respective population $q_k$ ($N$) of the $N$-electronic system of k atomic site, as[13,14]

$$f_k^+ = q_k(N+1) - q_k(N) \tag{6a}$$

and

$$f_k^- = q_k(N) - q_k(N-1). \tag{6b}$$

In the present paper the Fukui functions are calculated in terms of the orbital coefficients of the neutral species.[15]

During a chemical reaction, an electrophile or a nucleophile faces both attractive as well as repulsive forces as an atom/a functional group/a molecule contains both electrons and nucleus (nuclei). Concepts of various difference reactivity descriptors, both intramolecular and intermolecular, local as well as global, have been proposed essentially to highlight the electrophilicity of a system relative to its own nucleophilicity or that of the partner. They include dual descriptor,[16] electrophilicity difference,[17] electrophilicity excess,[18] multiphilic descriptor,[19] net electrophilicity index,[20] net reactivity index,[21] local hypersoftness[22] *etc.* It should be noted that these descriptors may not be adequate in explaining charge-controlled reactions[23,24] (*e.g.* hard–hard interactions). Molecular electrostatic potential or charge based descriptors would be useful in those cases.

In the present communication we propose a new reactivity difference descriptor ($R_k$) which is able to characterize local electrophilic/nucleophilic activation within an organic molecule, that may encompass a wide variety of systems including ambiphilic reagents and a large class of organic reactions.

The definition of $R_k$ is given by the following three conditions to identity the centers with electrophilic ($R_k$ = +n.nn) or nucleophilic ($R_k$ = −n.nn) behavior as well as the ambiphilic ($R_k$ = ±n.nn) behavior in addition to eliminate the centers with marginal reactivity:

$$\begin{aligned}
&\text{(a) if } (1 < \omega_k/N_k < 2) \text{ or } (1 < N_k/\omega_k < 2) \\
&\quad \text{then } R_k \approx (\omega_k + N_k)/2 \quad \Rightarrow \quad \text{ambiphilic } (R_k = \ \pm \text{ n.nn}) \\
&\text{(b) else } R_k \ \approx \ (\omega_k - N_k) \\
&\quad \text{where } R_k > 0 \quad \Rightarrow \quad \text{electrophilic } (R_k = +\text{n.nn}) \\
&\quad \text{and } R_k < 0 \quad \Rightarrow \quad \text{nucleophilic } (R_k = -\text{n.nn}) \\
&\text{(c) if } |R_k| \ < \ 0.1, \quad \text{then } R_k = 0.
\end{aligned}$$

In the $R_k$ index, the sign (+, −, ±) indicates the electrophilic or/and nucleophilic character of the center k, while the magnitude n.nn provides a measure of the local activation. We further explored if the proposed $R_k$ index could be suitable for a wider range of molecular systems displaying electrophilic and/or nucleophilic behavior, participating in polar cycloaddition reactions.[17,25]

## Results and discussion

First, an analysis of the local reactivity difference $R_k$ index in fifteen common neutral organic molecules participating in polar cycloaddition reactions will be performed. Then the ambiphilic behavior of dimethyl 2,3-dimethylenesuccinate **16** in polar Diels–Alder reactions will be analyzed using the $R_k$ molecular maps of the reagents.

### (a) Analysis of the local reactivity difference $R_k$ index in common neutral organic molecules participating in polar cycloaddition reactions

Global electrophilcity $\omega$ and nucleophilcity $N$ indices, local electrophilcity $\omega_k$ and nucleophilicity $N_k$, and local reactivity difference $R_k$ indices at the most reactive centers of fifteen common neutral organic molecules participating in polar cycloaddition reactions[17,25,26] are given in Table 1, while the structures of the corresponding molecules together with the most significant $R_k$ values are depicted in Fig. 1. In this figure, red, blue and green colors have been chosen to mark the electrophilic, nucleophilic and ambiphilic activations, respectively. Just as the global electrophilicity and nucleophilicity indices, the electronic local activation given by the local reactivity difference $R_k$ index can be classified as strong, moderate and marginal. For electrophilic and ambiphilic activations we can consider a strong activation if $|R_k|$

**Table 1** Local reactivity difference index $R_k$ for common organic molecules involved in polar cycloaddition reactions[a]

| | $\omega$ | $N$ | k | $\omega_k$ | $N_k$ | $R_k$ |
|---|---|---|---|---|---|---|
| **1** | 5.96 | 0.00 | C | 1.53 | 0.00 | +1.53 |
| | | | C | 1.53 | 0.00 | +1.53 |
| **2** | 3.24 | 0.98 | C1 | 0.40 | 0.02 | +0.38 |
| | | | C2 | 0.77 | 0.04 | +0.73 |
| **3** | 3.20 | 1.92 | C(O) | 1.06 | 0.08 | +0.99 |
| | | | C2 | 1.14 | 0.11 | +1.03 |
| **4** | 2.82 | 0.65 | C1 | 0.59 | 0.13 | +0.46 |
| | | | C2 | 1.41 | 0.22 | +1.19 |
| **5** | 2.61 | 1.07 | C1 | 0.20 | 0.01 | +0.19 |
| | | | C2 | 0.72 | 0.01 | +0.72 |
| **6** | 2.44 | 2.59 | C1 | 0.08 | 0.32 | −0.24 |
| | | | C2 | 0.45 | 1.06 | ±0.75 |
| **7** | 1.84 | 2.12 | C(O) | 0.50 | 0.10 | +0.40 |
| | | | C2 | 0.68 | 0.02 | +0.66 |
| **8** | 1.74 | 1.26 | C1 | 0.46 | 0.34 | ±0.40 |
| | | | C2 | 0.82 | 0.46 | ±0.64 |
| **9** | 1.05 | 2.83 | C1 | 0.34 | 0.93 | −0.60 |
| | | | C2 | 0.18 | 0.47 | −0.29 |
| **10** | 0.94 | 2.94 | C1 | 0.27 | 1.11 | −0.83 |
| | | | C2 | 0.15 | 0.53 | −0.39 |
| | | | C3 | 0.19 | 0.37 | −0.19 |
| | | | C4 | 0.31 | 0.81 | −0.50 |
| **11** | 0.93 | 3.13 | C1 | 0.28 | 0.93 | −0.65 |
| | | | C2 | 0.14 | 0.64 | −0.49 |
| | | | C3 | 0.17 | 0.42 | −0.25 |
| | | | C4 | 0.30 | 0.97 | −0.67 |
| **12** | 0.83 | 3.37 | C1 | 0.24 | 1.15 | −0.91 |
| | | | C2 | 0.13 | 0.52 | −0.39 |
| **13** | 0.42 | 3.20 | C1 | 0.20 | 0.65 | −0.45 |
| | | | C2 | 0.18 | 1.51 | −1.32 |
| **14** | 0.31 | 3.64 | C1 | 0.10 | 1.34 | −1.24 |
| | | | C2 | 0.03 | 0.47 | −0.44 |
| **15** | 0.21 | 4.28 | C1 | 0.09 | 0.35 | −0.25 |
| | | | C2 | 0.08 | 1.81 | −1.73 |

[a] The compounds are ordered by decreasing electrophilicity $\omega$ power. $R_k$ = +n.nn values correspond to electrophilic centers, $R_k$ = −n.nn values correspond to nucleophilic centers, and $R_k$ = ±n.nn values correspond to ambiphilic centers.

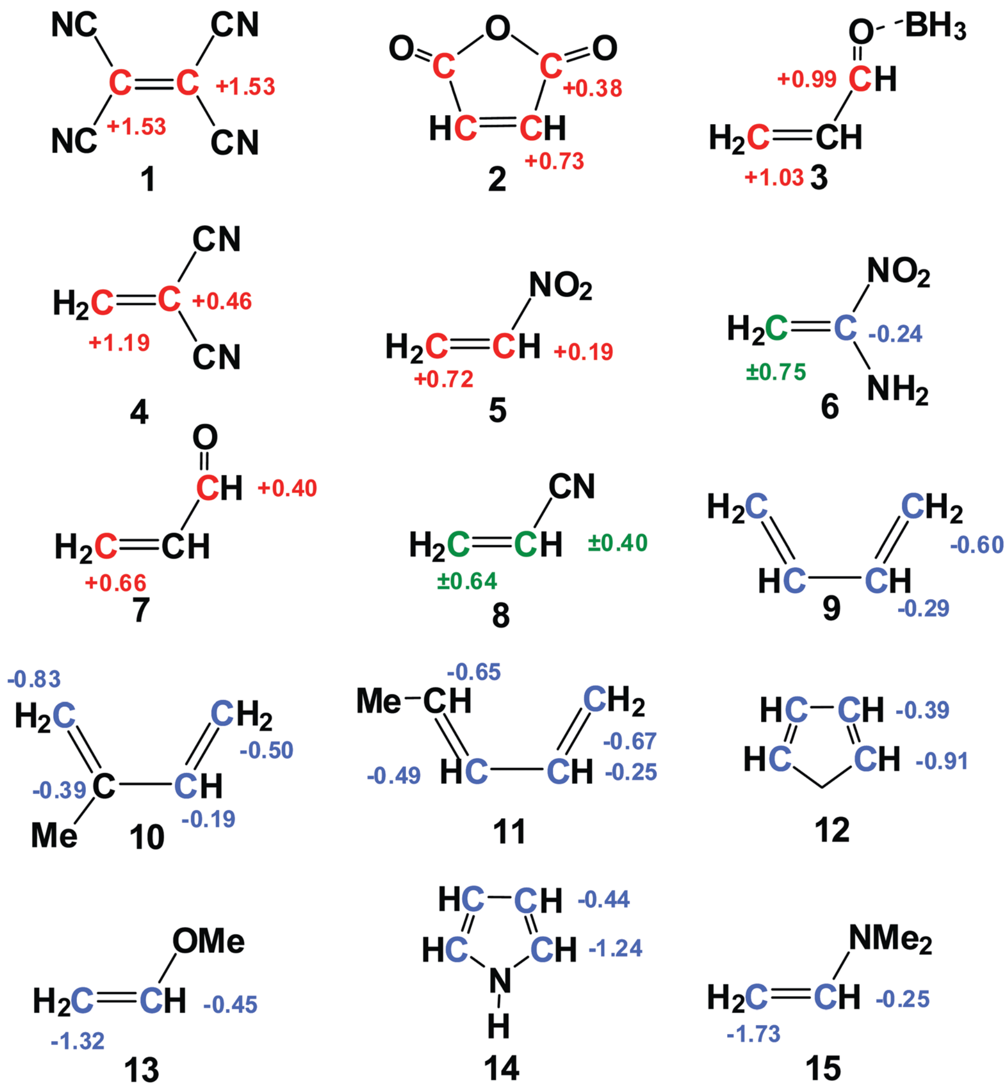


**Fig. 1** Local reactivity difference index $R_k$ for common organic molecules involved in polar cycloaddition reactions. $R_k$ = +n.nn in red corresponds to electrophilic centers, $R_k$ = −n.nn in blue corresponds to nucleophilic centers, and $R_k$ = ±n.nn in green corresponds to ambiphilic centers.

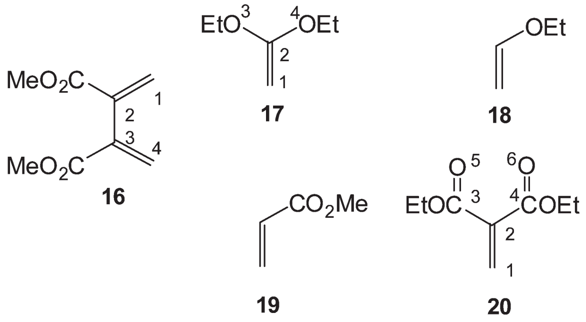
> 0.7 eV, moderate if $0.4 < |R_k| < 0.7$ eV, and marginal if $|R_k| < 0.4$ eV, while for nucleophilic activation we can consider a strong activation if $|R_k| > 1.5$ eV, moderate if $1.5 < |R_k| < 1.0$ eV and marginal if $|R_k| < 1.0$ eV. Note that the global electrophilicity and nucleophilicity scales do not have the same references.

The fifteen compounds given in Table 1 are ordered according to decreasing electrophilicity ($\omega$) values. For most of them, presenting a single substitution, the global nucleophilicity $N$ index increases on going towards the bottom of Table 1. A first analysis of the $R_k$ values given in Fig. 1 shows that whereas molecules (**1–7**) presenting electrophilic activated centers (red color) are located at the top of the table, those (**9–15**) presenting nucleophilic activated centers (blue color) are located at the bottom of the table, in clear agreement with the global electrophilic/nucleophilic behavior of these molecules. Molecules **6** and **8** presenting ambiphilic centers (green color) are located in the middle of the table. Therefore, the $R_k$ index consistently accounts for local electrophilic and nucleophilic activation in electrophilic and nucleophilic molecules.

Analysis of the most electrophilic C2 center in the monosubstituted ethylenic series **3**, **5**, **7** and **8**, and the most nucleophilic C2 center in the monosubstituted ethylenic series **13** and **15**, indicates that the absolute value of the $R_k$ index decreases on going from **3** to **8**, and increases on going from **13** to **15**, a similar trend to that followed by the global electrophilicity and nucleophilicity indices of these series. On the other hand, while compounds **1–6** present a strong electrophilic activation at the most activated center, $|R_2| > 0.7$ eV, compound **15** presents a strong nucleophilic activation at the most activated center $|R_2| > 1.5$ eV. Consequently, the $R_k$ index accounts for local activation when we compare electrophilic and nucleophilic molecules. This means that the best polar interactions will take place between the C1 center of **1**, $R_1$ = +1.53 eV, and the C2 center of **15**, $R_2$ = −1.73 eV. Note that they are the most electrophilic and nucleophilic molecules of these series; $\omega$ = 3.20 eV (**3**) and $N$ = 4.28 eV (**15**).

Within the asymmetrically substituted electron-deficient ethylenes **3–7**, substitution at the C1 position electrophilically activates the C2 center. On the other hand, for α,β-unsaturated carbonyl derivatives **3** and **7**, the $R_k$ index correctly predicts a larger electrophilic activation at the conjugated C2 position than at the carbonyl C(O) center. Note that coordination of the $BH_3$ Lewis acid to acrolein **7**, electrophilically activates the C2 position in complex **3**, $R_2$ = +1.03 eV, relative to that in acrolein **7**, $R_2$ = +0.66 eV. For the cyanoethylene series **1**, **4** and **8**, the $R_k$ index also predicts an enhanced local electrophilic activation with the cyano substitution in the ethylenic framework: $R_2$ = +1.53 eV at **1**, $R_2$ = +1.19 eV at **4** and $R_2$ = ±0.64 eV at **8**.[26] Interestingly, in cyanoethylene **8** the $R_k$ index affords an ambiphilic value at C2 similar to that in acrolein **7**. Note that both molecules have similar global electrophilicity values; $\omega$ = 1.84 eV (**7**) and $\omega$ = 1.74 eV (**8**). For captodative ethylene **6**, the local $R_k$ index also correctly predicts an ambiphilic behavior at the ethylenic C2 center, $R_2$ = ±0.75 eV.[10]

For asymmetrically substituted electron-rich ethylenes **13** and **15**, the $R_k$ index correctly predicts a higher nucleophilic activation at the C2 position, which increases with the increasing electron-releasing character of the substituent present in C1; $R_2$ = −1.32 eV at **13** and $R_2$ = −1.73 eV at **15**. Interestingly, the $R_k$ index predicts the expected nucleophilic activation in the 1,3-butadiene series **9**, **10** and **11**. Thus, while in 2-methyl-1,3-butadiene **10** the most nucleophilic activation takes place at the C1 position, $R_1$ = −0.83 eV, at 1-methyl-1,3-butadiene **11** this takes place at the C4 position, $R_4$ = −0.67 eV.[11b] Note that these positions are more nucleophilically activated than the C1 position in 1,3-butadiene **9**, $R_1$ = −0.60 eV, as a consequence of the electron-releasing character of the methyl group. Finally, for cyclopentadiene **12** and pyrrole **14**, the $R_k$ index predicts a larger nucleophilic activation at C1 than at the C2 center. In addition, the C1 position of pyrrole **14**, $R_1$ = −1.24 eV, is more nucleophilically activated than the C1 position of cyclopentadiene **12**, $R_1$ = −0.91 eV. This finding accounts for the high reactivity of the former in polar reactions.



**Scheme 1** Reactants involved in Spino's Diels–Alder reaction

**Table 2** Local reactivity index $R_k$ for reagents involved in the Spino's Diels–Alder reactions of diene **16** (see Scheme 1)[a]

| | $\omega$ | $N$ | k | $\omega_k$ | $N_k$ | $R_k$ |
|---|---|---|---|---|---|---|
| **20** | 1.71 | 1.92 | C1 | 0.77 | 0.06 | +0.71 |
| | | | C2 | 0.33 | 0.14 | +0.19 |
| | | | O5 (O6) | 0.13 | 0.67 | −0.54 |
| **16** | 1.60 | 2.38 | C1 (C4) | 0.47 | 0.65 | ±0.56 |
| | | | C2 (C3) | 0.13 | 0.40 | −0.26 |
| **17** | 0.41 | 3.11 | C1 | 0.17 | 1.58 | −1.41 |
| | | | C2 | 0.17 | 0.65 | −0.48 |
| | | | O3 (O4) | 0.01 | 0.33 | −0.32 |

[a] The compounds are ordered by decreasing electrophilicity $\omega$ power. $R_k$ = +n.nn values correspond to electrophilic centers, $R_k$ = −n.nn values correspond to nucleophilic centers, and $R_k$ = ±n.nn values correspond to ambiphilic centers.

### (b) Analysis of the ambiphilic reactivity of dimethyl 2,3-dimethylenesuccinate 16

In order to illustrate the utility of the local reactivity difference index $R_k$ in the study of polar reactions, we have selected an interesting example of a Diels–Alder reaction experimentally studied,[27] for which the frontier orbital molecular (FMO) theory[28] could not explain the reactivity.

In 2004, Spino *et al.* reported an experimental study of the Diels–Alder reactions of dimethyl 2,3-dimethylenesuccinate **16** with a wide variety of electron-rich ethylenes, including 1,1-diethoxyethene **17** and ethyl vinyl ether **18**, and electro-deficient ethylenes, including methyl acrylate **19** and diethyl 2-methylenemalonate **20** (see Scheme 1).[27] Interestingly, they observed that the fastest reaction corresponded to the reaction between the electron-deficient diene **16** and the electron-rich ethylene **17**. However, the reaction between the electron-deficient diene **16** and the electron-deficient dienophile **20** was faster than that involving the electron-rich monosubstituted dienophile **18**.[27] FMO theory[28] was used to predict the reactivity of these reagents in Diels–Alder reactions. Spino *et al.* concluded that, in normal Diels–Alder reactions, the FMO theory[28] could predict the relative reactivity, but in the case of inverse-electron-demand ones, it could not.

Subsequent DFT studies[29] on these reactions allowed for an interpretation of the experimental results based on the polar Diels–Alder model: within the electrophilicity scale, a molecule will behave as an electrophile against any molecule situated below it. However, the same molecule will behave as a nucleophile towards molecules located above it in the aforementioned scale.[29a] A further ELF analysis of these polar Diels–Alder reactions allowed for the explanation of the electrophilic/nucleophilic behavior of diene **16**.[29b] Along a two-center interaction, the most favorable channel is that involving the most electrophilic and nucleophilic centers of each reagent.[25] When diene **16** acts as an electrophile, the most electrophilic center is one of the two terminal C1 and C4 centers of the dienic system, which are conjugated to one of the two electron-withdrawing carboxylate groups present in C2 and C3, $\omega_1$ = $\omega_4$ = 0.47 eV. (see Table 2). However, when diene **16** reacts with a stronger electrophile, such as **20**, it must act as nucleophile, and in this case both carbons are also the most nucleophilic center of this molecule, $N_1$ = $N_4$ = 0.65 eV (see Table 2). In this case, along a polar reaction the conjugated carboxylate group presents in C3 twists, disabling its electron-withdrawing character.[29a]

Analysis of the local reactivity difference $R_k$ indices in the reagents allows for an easy explanation of the ambiphilic behavior of diene **16** toward both electron-rich and electron-deficient ethylenes such as **17** and **20** in polar reactions. As expected, electron-rich ethylene **17** has a larger nucleophilic activation at

C1, $R_1$ = −1.41 eV, than at $C_2$, $R_2$ = −0.48 eV, and electron-deficient ethylene **20** has a larger electrophilic activation at C1, $R_1$ = +0.71 eV, than at $C_2$, $R_2$ = +0.19 eV (see Fig. 2). Note that in both molecules, the ethylenic C1 centers present high nucleophilic and electrophilic activation.

Interestingly, the $R_k$ molecular map of reactivity[30] (RMMR) of diene **16** shows that the terminal C1 and C4 centers of the diene system have the same ambiphilic activation, $R_1 = R_4 = \pm 0.56$ eV. That is, diene **16** can participate in polar reactions *via* two-center interactions towards nucleophilic and electrophilic species. Note that the ethylenic C1 centers of dienophiles **17** and **20** present stronger activation than the terminal C1 and C4 centers of diene **16**. If we symmetrically divide diene **16** through the C2–C3 bond, we obtain two ethylene frameworks which resemble captodative ethylene **6**, in which the C1 center has ambiphilic activation (see Fig. 1). This feature can be understood if we consider the carboxylate in C2 as the electron-withdrawing group and the ethylene C3═C4 framework as the electron-releasing group.[10a]

A comparison of the sum of the absolute values of $R_k$ at the most electrophilic C1 center of diene **16** and at the most nucleophilic C1 center of electron-rich ethylene **18**, 0.56 + 1.41 = 1.97 eV, and the sum of the absolute values of $R_k$ at the most nucleophilic C1 center of diene **16** and at the most electrophilic C1 center of electron-deficient ethylene **17**, 0.56 + 0.71 = 1.27 eV, suggests that the first Diels–Alder reaction will be more polar, and consequently faster,[25] in clear agreement with the experimental data.[27]

During the completion of the present work we have studied the mechanism of the *N*-heterocyclic carbene (NHC) catalyzed intramolecular Stetter reaction of salicylaldehyde **21** to yield chromanone **23** (see Scheme 2).[31]

Analysis of the RMMR of the corresponding Breslow intermediate **IN** shows that the most favorable nucleophilic/electrophilic interaction along the intramolecular Michael addition takes place between the *umpolung* carbonyl C1 carbon, $R_1$ = −1.63 eV, and the β conjugated C2 carbon, $R_2$ = +0.45 eV, allowing the formation of the C1–C2 new bond present in chromanone **23**. Note that the $R_k$ index predicts that these carbons are the most nucleophilic and electrophilic centers respectively of Breslow intermediate **IN** (Fig. 3).

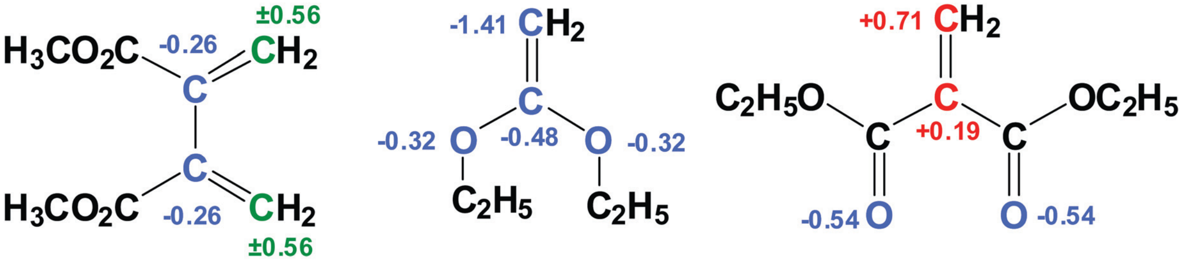
We can conclude that the RMMR of the reagents involved in polar reactions can not only explain the regioselectivity and chemoselectivity, but also the reactivity based on two-center electrophilic–nucleophilic interactions.[25,31] Note that in the cases of diene **16**, the FMO theory[28] is not able to explain its ambiphilic reactivity.

## Conclusions

From this preliminary analysis we can conclude that the proposed local difference $R_k$ index is able to predict the local electrophilic or/and nucleophilic activation within an organic molecule. Together with the electrophilic or/and nucleophilic behavior of the center k given by the sign, the magnitude of the $R_k$ index accounts for the extent of the electronic activation, a characteristic that allows for the use of this index as a semiquantitative measure of the molecular reactivity in polar processes.

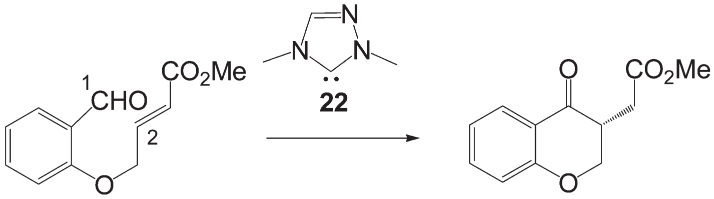
## Computational details

All calculations were carried out with the Gaussian 03 suite of programs.[32] DFT calculations were carried out using the



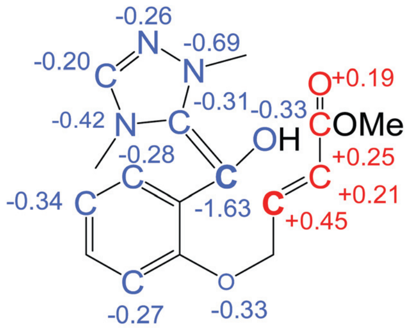
16 17 20

**Fig. 2** RMMRs of some reagents involved in the Spino's Diels–Alder reactions of diene **16** (see Scheme 1). $R_k$ = +n.nn in red corresponds to electrophilic centers, $R_k$ = −n.nn in blue corresponds to nucleophilic centers, and $R_k$ = ±n.nn in green corresponds to ambiphilic centers. $|R_k|$ values below 0.1 eV are not given.



21 23

**Scheme 2** Intramolecular Stetter reaction of salicylaldehyde **21** to yield chromanone **23**.



**IN**

**Fig. 3** RMMRs of Breslow intermediate **IN** associated with the NHC-catalyzed intramolecular Stetter reaction of salicylaldehyde **21** (see Scheme 2). $R_k$ = +n.nn in red corresponds to electrophilic centers, $R_k$ = −n.nn in blue corresponds to nucleophilic centers, and $R_k$ = ±n.nn in green corresponds to ambiphilic centers. $|R_k|$ values below 0.1 eV are not given.

B3LYP[33] exchange-correlation functionals, together with the standard 6-31G(d) basis set.[34] Optimizations were carried out using the Berny analytical gradient optimization method.[35]

The global electrophilicity index,[4] $\omega$, is given by the simple expression $\omega = (\mu^2/2\eta)$ (eV), in terms of the electronic chemical potential $\mu$ and the chemical hardness $\eta$. Both quantities are calculated in terms of HOMO and LUMO energies, $E_{\mathrm{HOMO}}$ and $E_{\mathrm{LUMO}}$, using eqns (2) and (3), respectively. The nucleophilicity index, $N$, based on the HOMO energies obtained within the Kohn–Sham scheme,[9] is calculated using eqn (4). This nucleophilicity scale takes tetracyanoethylene (TCE) as a reference. Local electrophilicity[11] and nucleophilicity[12] indices, $\omega_k$ and $N_k$, were evaluated using the following expressions: $\omega_k = \omega.f_k^+$ and $N_k = N.f_k^+$, where $f_k^+$ and $f_k^-$ are the Fukui functions for nucleophilic and electrophilic attacks, respectively.[15] It is expected that the qualitative trends will remain more or less unaltered in case we change the level of theory and/or basis sets. It may, however, be noted that $\omega$, $N$ and $f_k^{\pm}$ will be affected by different extents for that change.

## Acknowledgements

LRD is grateful to the Spanish Government (project CTQ2009-11027/BQU). SD thanks CSIR, New Delhi for a Senior Research Fellowship. PKC thanks DST, New Delhi for Sir J. C. Bose Fellowship.

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