

SYN-ANTI ISOMERISM IN THE 1,3-DIPOLAR CYCLOADDITION TO *CIS*-3,4-DISUBSTITUTED CYCLOBUTENES. 4. INTRAMOLECULAR INTERACTIONS

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Ab initio (4-31G) molecular geometry optimizations on *cis*-3,4-disubstituted cyclobutenes show that the extent and direction of their ground-state pyramidalization depend on the type of substituents and on whether these substituents are part of a ring condensed on to the cyclobutene moiety. Thus, electron-withdrawing substituents such as Cl and OMe bring about an out-of-plane *anti* bending of the olefinic hydrogens, whereas cyclobutenes condensed on to small carbocyclic rings exhibit high *syn* bending. Intramolecular interactions are analysed in the frame of a new model where the interactions arise from the energy matrix elements between the hybrid atomic orbitals involved in the different bonds. The analysis is carried out by C-INDO calculations on deformed molecules (with the olefinic hydrogens forced out-of-plane by $\pm 20^\circ$). These latter calculations reveal that non-planarity of the double bond occurs in the direction of increasing interactions between the hybrid atomic orbitals involved in the σ -allylic bonds and in the π -bond. The increase in this kind of interaction can also explain non-planarity in norbornene, 7-oxanorbornene, 5,6-dioxanorbornene and 5,6-dioxabicyclo [2.2.2] oct-2-ene. The results strongly suggest that pyramidalization and the related energy asymmetry of out-of-plane bending of olefinic hydrogens are important factors in governing facial selectivity of 1,3-dipolar cycloadditions to *cis*-3,4-disubstituted cyclobutenes.

INTRODUCTION

The way the allylic substituent effectively controls or directs π -facial selectivity in cycloadditions has recently attracted considerable interest.^{1,2} The difficulty rests in the fact that many different factors are likely to intervene with different weights in different contexts. Indeed, both direct intermolecular interactions (steric and hydrogen bonding effects, dipole-dipole and orbital interactions) with the incoming reactant and intramolecular features (π -bond pyramidalization, orbital tilting, non-equivalent orbital extension) can be taken, separately or in various combinations, as responsible for the diastereofacial selectivity of the various reactions. Wide rationalizations have recently been advanced either by the use of a steric model (Houk's staggered model)^{3,i,j} or by the use of an electrostatic model (Hehre's modelling treatment);⁴ in spite of their wide applicability and success, these do not appear to

explain easily the stereochemistry of attack experienced by the consistent group of *cis*-3,4-disubstituted cyclobutenes whose 1,3-dipolar cycloadditions we are investigating. On the contrary, in agreement with our preliminary work,^{2g} we shall show that non-planarity induced intramolecularly by the allylic substituent into the olefinic moiety, and the related concept of π -bond pyramidalization lends itself as the most reasonable candidate to explain the facial selectivity of cyclobutene 1,3-dipolar cycloaddition, particularly when steric and electrostatic intermolecular interactions are minimized by an accurate selection of substituents and of reactant 1,3-dipoles.

The theoretical results reported in this paper concern *cis*-disubstituted cyclobutenes and related molecules, tested with the aim of exploring the role of the above effects in a variety of graded situations. Moreover, the choice of the cyclobutene model, the symmetric *cis*-disubstitution and the concerted cycloaddition enabled us to avoid a number of problems concerning the distinction between regioisomers and the possibility of variable reaction mechanisms. Finally, the use of rigid

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systems makes it possible to avoid the cumbersome presence of many conformations.

The dipolarophiles under study display a high variability in structure and reactivity; in fact, they include cyclobutenes with open and cyclic 3,4-disubstitution, bridges of different sizes and equal-length bridges with and without heteroatoms; moreover, when reacted, e.g., with diazomethane, they cover the complete range of facial selectivity, from 100% *syn* diastereoselectivity to 100% *anti* diastereoselectivity through mixtures with various *syn*:*anti* ratios (for an alternative nomenclature for facial selectivity, see Ref. 5). Furthermore, different 1,3-dipoles were employed, including 'electron-rich,' 'sterically and electrostatically neutral' diazomethane and the 'electron-poor' phenylglyoxylonitrile oxide, 1,3-dipoles with a high dipole moment such as benzonitrile oxide or nitrones and the 'sterically demanding' 2-diazopropane. Moreover, owing to the central role played by norbornene in experimental and theoretical studies of facial selectivity,^{1b,3c,d,6} we deemed it necessary to extend our studies to norbornene and 7-oxa- and 5,6-dioxanorbornene. For the sake of comparison, bicyclo[2.2.2]oct-2-ene and 5,6-dioxabicyclo[2.2.2]oct-2-ene were also investigated. Figure 1 shows the structures of all the molecules studied.

For reasons of simplicity of presentation, the numbering of the cyclobutene ring is the same for all of the cyclobutene derivatives, hence in many cases it does not follow IUPAC rules. The same is true for the norbornene and bicyclo[2.2.2]octene rings.

Throughout we shall use the *syn* descriptor for attack on the cyclobutene double bond near the allylic substituents.⁵ In the case of norbornene, 7-oxanorbornene and 5,6-dioxanorbornene, *syn* attack refers to attack next to the monoatomic bridge, and in 5,6-dioxabicyclo[2.2.2]oct-2-ene to attack next to the heteroatomic bridge. The same system of descriptors is used for out-of-plane bending, e.g. in *syn* bent

cyclobutenes the olefinic hydrogens bend towards the substituents and the bending angle α is given a plus sign. Thus negative α values indicate *anti* bending.

RESULTS AND DISCUSSION

Experimental *syn*:*anti* ratios and geometrical data

The experimental *syn*:*anti* ratios for 1,3-dipolar cycloadditions of cyclobutenes 2-4 with four representative 1,3-dipoles reported so far are collected in Table 1. The trends in Table 1 also hold for the reactions of azomethine imides and nitrile imides.^{2f,7} Moreover, bicyclopentene 1a has been reported to afford only *anti* adducts in reactions with benzonitrile oxide, benzonitrile phenylimide, and diphenyldiazomethane.^{2h}

High *syn* selectivity is observed for X = OAc, OMe, OSO₂Me and Cl, whereas in the case of cyclic disubstitution, even with heteroatoms, there is a shift towards *anti* adducts. Noteworthy is the fact that the type II 1,3-dipoles, in particular the 'electron poor' phenylglyoxylonitrile oxide, exhibit a behaviour very similar to that of type I 'electron rich' diazomethane. It is evident that, whatever the 1,3-dipole, the dipolarophiles tend to impose their own stereochemical demand, that is, some intrinsic feature of cyclobutenes tends to guide facial selectivity.

Theoretical structures (optimum geometries) of cyclobutenes 1, 2a and b, 3a-e and 4a, c and d were calculated at the single-determinant level, with the 4-31G basis set and the Berny optimization procedure [convergence limits were as follows: maximum force 4.5, RMS force 3.0, maximum displacement 18.0, RMS displacement 12.0; internal units (hartree bohr radians) $\times 10^4$].⁸ (For previous STO-3G calculations on 1a and on bicyclo[2.2.2]hexadiene (2d), see Ref. 9. Moreover, STO-3G calculations have also been carried out on *cis*-3,4-difluorocyclobutene and a possible

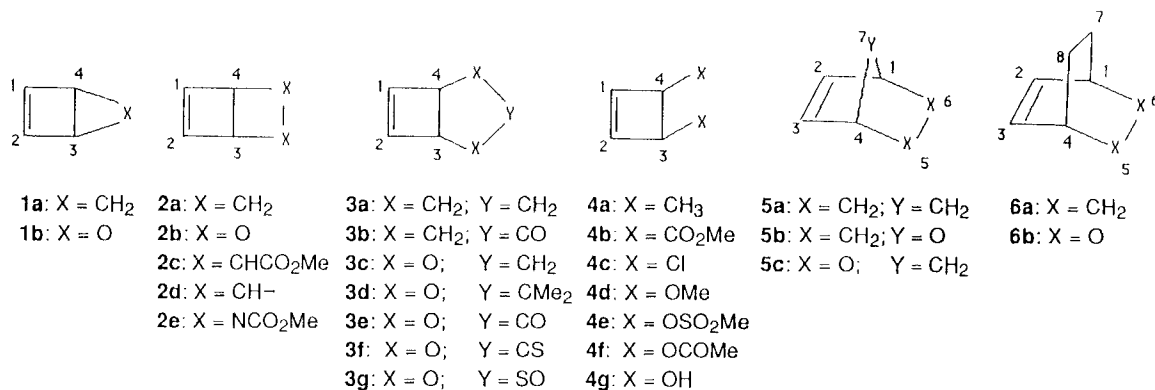
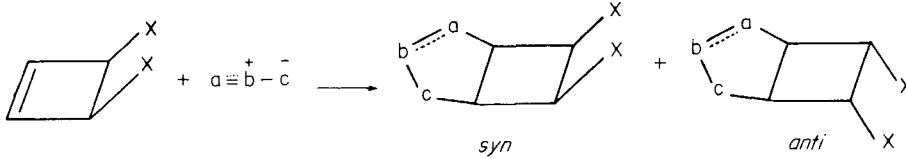


Figure 1. Structure of compounds

Table 1. Experimental *syn*:*anti* ratios^a


Dipolarophile	CH ₂ N ₂	(CH ₃)CN ₂	PhCOCNO	CH ₂ N(<i>t</i> -Bu)O
2c	0:100 ^b			
2d	9:91 ^d		0:100 ^{b,c}	
2e	0:100 ^d	0:100 ^d	0:100 ^{c,d}	
3a	0:100 ^c	0:100 ^f	0:100 ^e	0:100 ^f
3b			13:87 ^e	< 5:95
3c	0:100 ^c		0:100 ^e	0:100
3d	40:60 ^e	0:100	13:87 ^e	< 5:95
3e	36:64 ^c	9:91 ^f	34:66 ^c	2:98 ^f
3f	57:43	20:80		4:96
3g	60:40	10:90	36:64 ^g	7:93
4a	30:70 ^h			
4b	60:40 ⁱ	≤ 5:95 ^j	5:95 ^c	12:88 ^l
4c	94:6 ^j	30:70 ^j	78:22 ^m	73:27 ^{l,n}
4d	100:0	80:20	80:20 ^c	90:10
4e	100:0	87:13	88:12 ^c	91:9
4f	100:0 ^f	70:30 ^f	95:5 ^f	77:23 ^f
4g			87:13 ^{c,g}	97:3

^a *syn*:*anti* ratio refers to reactions carried out in diethyl ether or benzene at room temperature. Results not previously reported in the literature are unpublished data from our laboratory. (see also Ref. 2s)

^b Ref. 2o.

^c *syn*:*anti* ratio for the reaction with benzonitrile oxide.

^d Ref. 2i.

^e Ref. 10.

^f Ref. 7.

^g In refluxing benzene.

^h Ref. 2q.

ⁱ Compound **4b** has been previously reported (see Ref. 2b) to be unreactive with diazomethane.

^j Refs. 2a, b, s.

^k *syn*:*anti* ratio for the reaction with 3,4-dihydroisoquinoline *N*-oxide (Ref. 2d).

^l *syn*:*anti* ratio for the reaction with benzonitrile oxide = 48:52 in diethyl ether and 71:29 in acetonitrile (Ref. 2c).

^m *syn*:*anti* = 78:22 and 75:25 in boiling ethanol and acetonitrile, respectively (Ref. 2d).

correlation between olefinic hydrogen out-of-plane bending and facial selectivity have been briefly suggested.^{1f}) These are provided in Table 2. All *ab initio* calculations were performed with the Gaussian 82 package⁸ as implemented on a CRAY X-MP/48 computer.

The skeletal dihedral angle α (Table 2) varies from 7.1° and 7.3° (*syn* bending) in bicyclopentenes **1a** and **1b**, respectively, to -2.2° (*anti* bending) in dichlorocyclobutene **4c**, thus revealing a definite influence of the substituents on the sign and extent of double bond non-planarity. The plot of the *anti*:*syn* ratio of diazomethane cycloaddition vs α (Figure 2) clearly shows that there is a good parallelism between non-planarity and facial selectivity in diazomethane cycloaddition.

Hence non-planarity of the double bond and the

related energy asymmetry of the out-of-plane bending of the olefinic hydrogens [on their way towards the transition state (TS), as clearly revealed (see below) by the difference in energies required to induce $+20^\circ$ and -20° hydrogen out-of-plane bending] can be invoked as the inherent facial bias of cyclobutenes. Figure 2, however, also reveals that, at least for small α , other structural features may be significant; thus, **3a** ($\alpha = 0.96^\circ$) and **3c** ($\alpha = 0.20^\circ$) could not reach complete 100% *anti* diastereoselectivity without the cooperation of the steric repulsions, due to their boat-like conformations ($\delta = 143.9^\circ$ and 152.8° , respectively) which hinder the *syn* approach, whereas for **3d** ($\alpha = -0.17^\circ$) and **3e** ($\alpha = 0.51^\circ$), owing to their nearly half-planar conformations ($\delta = 169.0^\circ$ and 174.3° , respectively), mixtures of *syn* and *anti* adducts are allowed.¹⁰ Further, when dimethylcyclobutene **4a** ($\alpha = -0.90^\circ$, *anti*:*syn*

Table 2. 4-31G optimum geometries (C_3 symmetry) of cyclobutenes **1**, **2a** and **b**, **3a-e**, **4a, c** and **d** and of cyclobutene (C_{2v} symmetry)^{a, b}

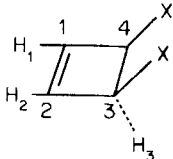
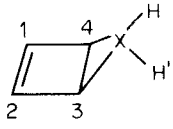
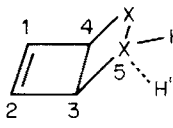
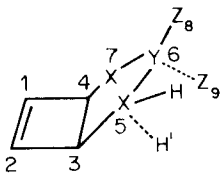
		Cyclobutene ring:		
		$A = C_1C_2$	$B = C_2C_3$	$C = C_3C_4$
		$D = C_1H_1$	$E = C_3H_3$	
		$K = C_1C_2C_3$	$J = C_2C_1H_1$	$I = C_2C_3H_3$
		$\alpha = C_3C_2C_1H_1$	$\gamma = C_1C_4C_3H_3$	
		Substituent X:		
		$a = C_3X$	$g = C_2C_3X$	$\beta = C_2C_3C_4X$
		Cyclobutene:		
		$A = 1.326$	$B = 1.524$	$C = 1.576$
		$D = 1.069$	$E = 1.082$	
		$K = 94.71$	$J = 133.46$	$I = 115.83$
		$\alpha = 0.00$	$\beta = \gamma = 116.33$	
		Energy = -154.6679		
	1a	$A = 1.330$	$B = 1.529$	$C = 1.521$
	X = C	$D = 1.068$	$E = 1.067$	
		$K = 93.59$	$J = 134.01$	$I = 126.87$
		$\alpha = 7.08$	$\gamma = 135.43$	
		$a = 1.517$	$g = 108.79$	$\beta = 114.16$
		$C_3XH = 119.32$	$C_3XH' = 116.38$	$HXH' = 114.63$
		$XH = XH' = 1.074$		
		Energy = -192.4152		
	1b	$A = 1.330$	$B = 1.531$	$C = 1.463$
	X = O	$D = 1.066$	$E = 1.064$	
		$K = 92.49$	$J = 134.42$	$I = 131.05$
		$\alpha = 7.29$	$\gamma = 147.23$	
		$a = 1.477$	$g = 106.28$	$\beta = 110.36$
		Energy = -228.1545		
	2a	$A = 1.329$	$B = 1.521$	$C = 1.580$
	X = C	$D = 1.070$	$E = 1.077$	
		$K = 94.74$	$J = 133.30$	$I = 119.17$
		$\alpha = 3.91$	$\gamma = 122.08$	
		$a = 1.562$	$g = 114.12$	$\beta = 114.25$
		$C_3X_5H = 115.30$	$X_6X_5H = 115.50$	$C_3X_5H' = 112.81$
		$HXH' = 108.57$		
		$XX = 1.557$	$XH = 1.080$	$XH' = 1.081$
		Energy = -231.4213		
	2b	$A = 1.329^c$	$B = 1.511$	$C = 1.540$
	X = O	$D = 1.070^c$	$E = 1.077^c$	
		$K = 94.00$	$J = 133.81$	$I = 123.55$
		$\alpha = 3.76$	$\gamma = 130.18$	
		$a = 1.484$	$g = 112.52$	$\beta = 112.64$
		$XX = 1.498$		
		Energy = -302.8521		
	3a	$A = 1342^d$	$B = 1.526$	$C = 1.586$
	boat	$D = 1.083^d$	$E = 1.094^d$	
	X = Y = C	$K = 94.59$	$J = 133.47$	$I = 115.70$
	Z ₈ = H	$\alpha = 0.96$	$\gamma = 116.51$	
	Z ₉ = H	$a = 1.533$	$g = 116.04$	$\beta = 115.79$
		$X_5YX_7 = 104.39$	$C_3X_5H = 111.09$	$C_3X_5H' = 111.09$
		$XYH = 109.76$	$HX_5H' = 107.35$	$X_5YZ_8 = 112.47$
		$X_5YZ_9 = 110.16$		
		$XY = 1.541$	$XH = XH' = YZ_8 = YZ_9 = 1.094^d$	
		$\delta = C_3X_5X_7Y = 143.95$		
		Energy = -270.4405		

Table 2. (Continued)

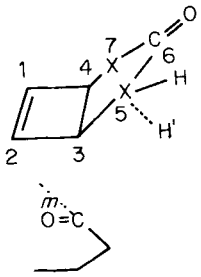
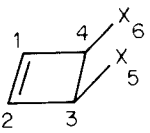
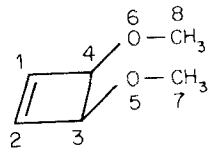
3a chair X = Y = C Z ₈ = H Z ₉ = H	$A = 1342^d$ $D = 1.083^d$ $K = 94.53$ $\alpha = 0.36$ $a = 1.538$ $X_5YX_7 = 104.73$ $YXH = 109.89$ $X_5YZ_9 = 109.64$ $XY = 1.542$ $\delta = C_3X_5X_7Y = 217.00$ Energy = -270.4344	$B = 1.528$ $E = 1.094^d$ $J = 133.49$ $\gamma = 116.01$ $g = 118.71$ $C_3X_5H = 111.59$ $HX_5H' = 107.33$ $XH = XH' = YZ_8 = YZ_9 = 1.094^d$	$C = 1.583$ $I = 115.39$ $\beta = 118.60$ $C_3X_5H' = 111.59$ $X_5YZ_8 = 112.79$
3c X = O Y = C Z ₈ = H Z ₉ = H	$A = 1342^d$ $D = 1.083^d$ $K = 94.26$ $\alpha = 0.20$ $a = 1.427$ $Z_8YZ_9 = 111.49$ $XY = 1.429$ $\delta = C_3X_5X_7Y = 152.85$ Energy = -341.9553	$B = 1.522$ $E = 1.094^d$ $J = 133.75$ $\gamma = 121.70$ $g = 116.18$ $X_5YZ_8 = 110.29$ $YZ_8 = YZ_9 = 1.094^d$	$C = 1.568$ $I = 119.27$ $\beta = 115.95$ $X_5YZ_9 = 109.33$
3d X = O Y = C Z ₈ = Me Z ₉ = Me	$A = 1342^d$ $D = 1.083^d$ $K = 94.14$ $\alpha = -0.17$ $a = 1.423$ $X_5YX_7 = 105.28$ $Z_8YZ_9 = 113.82$ $YZ_9H = 110.06$ $XY = 1.447$ $Z_8H = Z_9H = 1.094^d$ $\delta = C_3X_5X_7Y = 169.03$ Energy = -419.9284	$B = 1.522$ $E = 1.094^d$ $J = 133.86$ $\gamma = 120.54$ $g = 116.80$ $X_5YZ_8 = 110.19$ $YZ_8H = 110.06$ $HZ_9H = 108.87$ $YZ_8 = 1.510$	$C = 1.562$ $I = 118.39$ $\beta = 116.65$ $X_5YZ_9 = 108.50$ $HZ_8H = 108.87$ $YZ_9 = 1.510$
 3b X = C	$A = 1342^d$ $D = 1.083^d$ $K = 94.74$ $\alpha = 0.80$ $a = 1.527$ $X_5C_6X_7 = 110.01$ $C_6X_5H = 107.93$ $XC_6 = 1.517$ $m = 1.33$ Energy = -344.0262	$B = 1.524$ $E = 1.094^d$ $J = 133.61$ $\gamma = 116.50$ $g = 115.73$ $C_3X_5H = 112.74$ $HX_5H' = 107.24$ $CO = 1.209$ $\delta = C_3X_5X_7C_6 = 158.33$	$C = 1.594$ $I = 115.83$ $\beta = 115.48$ $C_3X_5H' = 112.74$ $X_5C_6O = 124.99$ $XH = XH' = 1.094^d$
3e X = O	$A = 1342^d$ $D = 1.083^d$ $K = 94.21$ $\alpha = 0.51$ $a = 1.440$ $X_5C_6X_7 = 109.44$ $X_5C_6 = 1.363$ $\delta = C_3X_5X_7C_6 = 174.31$ Energy = -415.5663	$B = 1.513$ $E = 1.094^d$ $J = 134.15$ $\gamma = 123.68$ $g = 114.56$ $X_5C_6O = 125.28$ $CO = 1.185$	$C = 1.564$ $I = 120.66$ $\beta = 114.26$

Table 2. (Continued)

	4a	$A = 1.342^d$	$B = 1.526$	$C = 1.590$
	X = Me	$D = 1.083^d$ $K = 94.66$ $\alpha = -0.90$ $a = 1.521$ HX ₅ H = 108.21, 107.52, 107.54 C ₃ X ₅ H = 111.68, 111.35, 110.36 C ₂ C ₃ X ₅ H ₁ = 47.30 X ₅ H = 1.094 ^d Energy = -232.6257	$E = 1.094^d$ $J = 133.51$ $\gamma = 113.08$ $g = 117.30$	$I = 113.17$ $\beta = 118.68$
	4c	$A = 1.342^d$	$B = 1.505$	$C = 1.562$
	X = Cl	$D = 1.083^d$ $K = 94.19$ $\alpha = -2.24$ $a = 1.862$ Energy = -1071.4799	$E = 1.094^d$ $J = 134.56$ $\gamma = 119.36$ $g = 114.75$	$I = 118.24$ $\beta = 115.82$
	4d	$A = 1.342^d$	$B = 1.512$	$C = 1.588$
		$D = 1.083^d$ $K = 94.67$ $\alpha = -1.43$ $a = 1.408$ C ₃ O ₅ C ₇ = 118.33 HC ₇ H = 108.89, 109.05, 109.05 O ₅ C ₇ = 1.421 C ₂ C ₃ OC ₇ = 163.21 Energy = -382.0769	$E = 1.094^d$ $J = 134.14$ $\gamma = 115.79$ $g = 113.18$ O ₅ C ₇ H = 106.64, 111.57, 111.57 C ₇ H = 1.094 ^d C ₃ OC ₇ H ₁ = 175.36	$I = 115.40$ $\beta = 113.67$

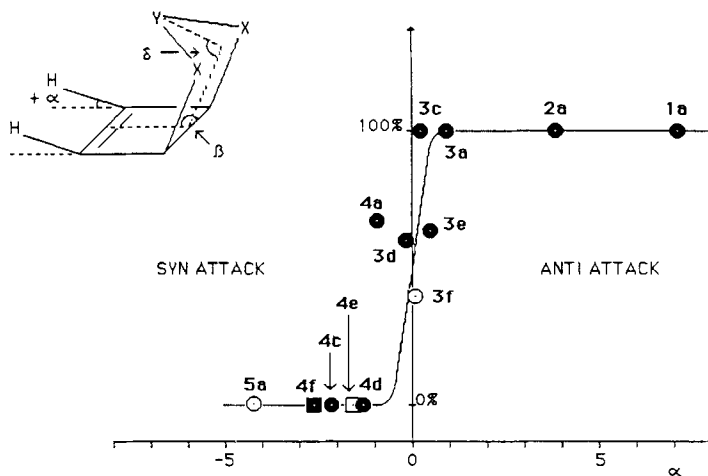
^d Energy in hartrees.^b Bond lengths in ångströms, angles in degrees. C₁C₂ etc. represent C-1-C-2 bonds etc.^c Assumed from the calculated geometry of **2a**.^d Assumed.

Figure 2. *Anti* addition (%) for the reaction of diazomethane with cyclobutenes vs. α . • 4-31G optimization (constraints: C, symmetry). ○ STO-3G optimization [constraints: C, symmetry, C=C, C(sp³)-H and C(sp²)-H bond lengths = 1.342, 1.094 and 1.083 Å, respectively]. ■ STO-3G optimization (constraints: C, symmetry; cyclobutene ring geometry assumed from the *cis*-3,4-dichlorocyclobutene experimental geometry and OAc geometry fixed to standard values). □ STO-3G optimization of α on the geometry taken from crystallographic data for **4e** (unpublished results) and with H in place of Me

7 : 3 mixture) and dimethoxycyclobutene **4d** ($\alpha = -1.43$, 100% *syn* selectivity) are compared, even allowing for a greater steric effect in the case of the dimethyl derivative, some further intermolecular effect of the heteroatom in favouring the *syn* attack cannot be excluded; it is also worth pointing out that in all cases in which dominance of *syn* attack on cyclobutenes was observed there were heteroatoms as substituents. This last factor, together with relevant intermolecular interactions, will be discussed in a following paper;²⁵ here we report some results and arguments about the intramolecular origin of non-planarity.

Intramolecular interactions and non-planarity

The structural features most related to the double bond non-planarity α are illustrated in Figure 3a and b for the hydrocarbons of our sample, norbornene (optimum geometry at the STO-3G level) having been added for completeness. The geometrical trend in Figure 3a could be attributed qualitatively either to the tendency to minimize 'torsional repulsions' (that is, the tendency of σ -bonds to prefer staggered conformations) or to hyperconjugative interactions between σ -bonds and π -bonds (that is, the tendency to maximize when stabilizing or minimize if this kind of interaction is repulsive). The relative merits of the two explanations are compared below.

Torsional repulsions

It can be seen that with respect to planarity, the olefinic C-H bonds are slightly rotated towards more staggered geometries. This could suggest that rotation, forced by σ -bond- σ -bond repulsions, tends to minimize torsional (Pitzer) strain between olefinic C-H bonds and allylic bonds. However, other structural features give significant indications against σ -bond- σ -bond repulsions as an exclusive cause of non-planarity. First, the olefinic C-H bonds are highly staggered with respect to both C-H and C-X allylic bonds even in the planar form; moreover, the olefinic bond angles H-1-C-1-C-4 and H-2-C-2-C-3 are very large ($>131^\circ$ in all of the cyclobutenes); also the bond angles C-1-C-4-H-4 and C-2-C-3-H-3 are fairly large (from 113.2° in dimethylcyclobutene **4a** to 126.9° in bicyclopentene **1a**), whereas bond angles C-1-C-4-X are small only in bicyclopentene and in its oxa derivative (108.8° and 106.3° , respectively) where, on the other hand, the olefinic C-H bonds bend towards the X substituent in the optimized structures. Thus compared with ethane (HCC = 111.6° , experimental) σ -bond- σ -bond repulsions in our system are smaller.

An even stronger argument comes from consideration of the dihedral angles β (C-2-C-3-C-4-X) in relation to the non-planarity angle α ; Figure 3b shows that the

larger is β , the larger are the *anti* bendings (with respect to X). This feature is better emphasized by model calculations on 'distorted' molecules where different β values are imposed and only α values are varied to satisfy energy optimization. As an example, Figure 3c reports the comparison between dimethylcyclobutene (II) and 'deformed' dimethylcyclobutenes (I and III). It does not seem easy to explain this relationship by σ -bond- σ -bond repulsions.

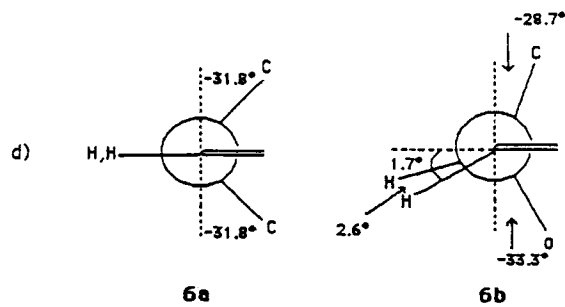
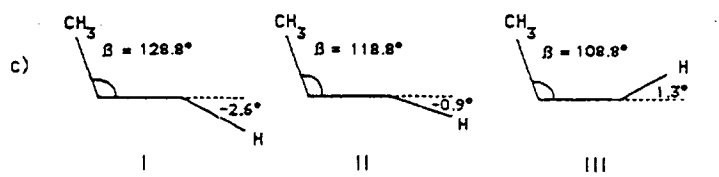
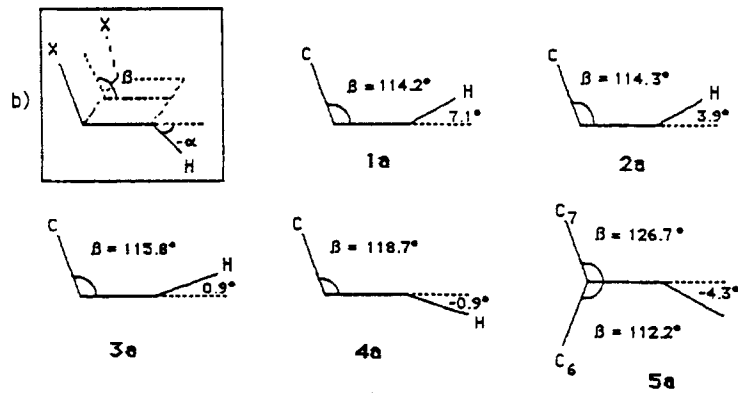
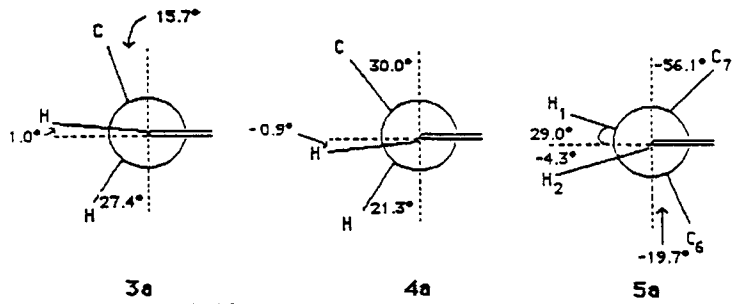
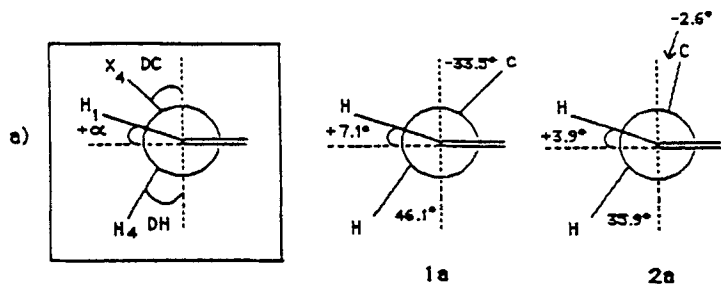
The case of norbornene **5a** (H-2-C-2-C-1 = 124.4° , C-2-C-1-H-1 = 116.0° , C-2-C-1-C-7 = 100.0° , C-2-C-1-C-6 = 106.6°) is decidedly different from that of cyclobutenes owing to the presence of C-1-H and C-4-H bonds. In fact, the dihedral angle H-1-C-1-C-2-H-2 = 29.0° in the planar form is such that the torsional effect of C-1-H and C-4-H on olefinic hydrogens could reasonably be invoked to explain *anti* bending.^{3,9} However, if we consider the case of bicyclooctene and its dioxo derivative, we find that in **6a** there is perfect eclipsing between olefinic and bridgehead C-H bonds and, even more important, in **6b** the olefinic C-H bonds bend towards the heteroatomic bridge (*syn*) together with the C-1-H and C-4-H bonds, maintaining almost perfect eclipsing with respect to each other (Figure 3d); it is worth adding that in **6b**, HCC bond angles, although large (H-2-C-2-C-1 = 122.1° and H-1-C-1-C-2 = 113.3° are the lowest values encountered in our systems (i.e., the torsional effect should be at a maximum).

The above arguments and results are not certainly sufficient to exclude any role of torsional repulsions in the pyramidalization of the olefins under study but, in our opinion, they are strong enough to call for alternative or additional effects.

Hyperconjugative interactions

A convincing explanation of the geometrical trends in Figure 3a-d can be qualitatively obtained by assuming that interactions between σ - and π -bonds are stabilizing and that out-of-plane bending is induced by the tendency to favour eclipsing of the p_π (or π -type) atomic orbitals of the olefinic carbons with the C-H and C-X σ -bonds at positions 3 and 4 of the cyclobutene ring (position 1 and 4 in norbornene and bicyclooctene frames) (Figure 4).

The tilting of the p_π orbitals, together with a modest pyramidalization, modifies their alignments with the above σ -bonds, the tilting being counteracted by the decrease in the double bond p_π - p_π overlap. Hence, in **1a** and **2a** both p_π -C-C and p_π -C-H interactions are increased by *syn* bending on the olefinic hydrogens, whereas in **3a** and **4a** the two interactions are favoured by opposite distortions so that small α values result from the competition. In the case of norbornene the prevailing *anti* distortion is favoured by p_π -C-1-C-6



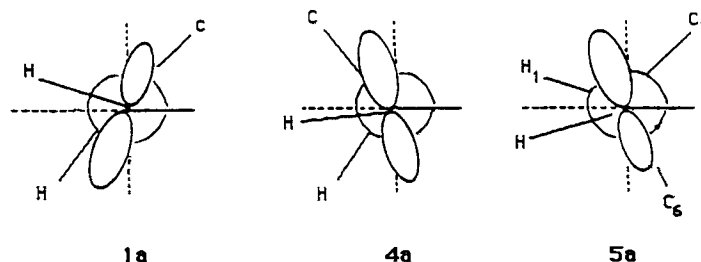


Figure 4. Pyramidalization and tilting of p_x atomic orbitals in **1a**, **4a** and **5a**

and p_π -C-1-H interactions, whereas a *syn* distortion would be assisted only by the increase in p_π -C-1-C-7.

Heteroatom substitution influences non-planarity, as illustrated in Figure 5 compared with Figure 3a (for previous STO-3G calculations on **5b** and **5c**, see Ref. 6g). Even though the effect of heteroatom substi-

tution is complex, the results can be easily understood, for most of the compounds in Figure 5, if it is assumed, as demonstrated in the next section, that p_π -C-O interactions introduce higher stabilizations than p_π -C-C interactions. Actually, there is no relevant change in α in **1b** and **2b** as compared with **1a** and **2a**,

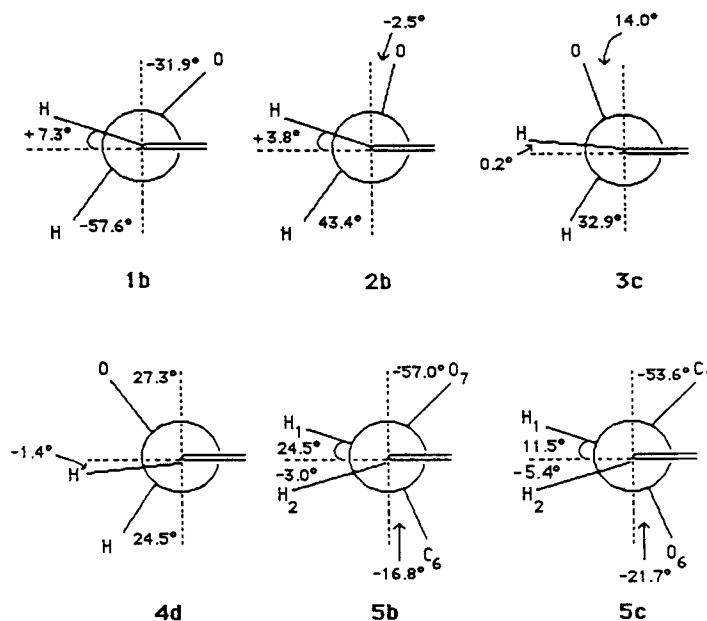


Figure 5. Newman projections along the C-1-C-4 bond of cyclobutenes **1b**, **2b**, **3c** and **4d** (4-31G optimized structures reported in Table 2) and along the C-2-C-1 bond of norbornenes **5b** and **5c** [STO-3G optimized structures with the following constraints: C_s symmetry, C=C, $C(sp^3)$ -H and $C(sp^2)$ -H bond lengths = 1.342, 1.094, and 1.083 Å, respectively], showing the dihedral angles DC and DH and the dihedral angle α

Figure 3. Structural features related to the non-planarity parameter α . (a) Newman projections along the C-1-C-4 bond of cyclobutenes **1a-4a** and along the C-2-C-1 bond of norbornene (**5a**). The reference plane for the dihedral angles DC and DH contains the C-1-C-4 bond (C-2-C-1 for norbornene) and is perpendicular to the cyclobutene plane. [4-31G optimized structures, reported in Table 2, for **1a-4a**, and STO-3G optimized structure for **5a** with the following constraints: C_s symmetry, C=C, $C(sp^3)$ -H, and $C(sp^2)$ -H bond lengths = 1.342, 1.094, and 1.083 Å, respectively]. (b) Lateral side view showing the dihedral angles β and α . (c) Relationship between β and α in distorted *cis*-3,4-dimethylcyclobutene (STO-3G). (d) Newman projections along the C-2-C-1 bond of bicyclo[2.2.2]oct-2-ene (**6a**) and of its dioxo derivative **6b** [STO-3G optimized structure with the following constraints: C_s symmetry, C=C, $C(sp^3)$ -H and $C(sp^2)$ -H bond lengths = 1.342, 1.094, and 1.083 Å, respectively]

respectively. However, also in **1b** and **2b** $p_{\pi}\text{-C-O}$ interactions are larger than related $p_{\pi}\text{-C-C}$ interactions in **1a** and **2a**, respectively. We may emphasize that in these two cases both $p_{\pi}/\text{C-X}$ and $p_{\pi}\text{-C-H}$ interactions favour *syn* bending and that C-X bonds in these compounds are highly bent.

It is noteworthy that the out-of-plane bending of olefinic hydrogens induced by oxygen substitution in bicyclooctene (Figure 3d), discussed in the preceding section, conforms well with the tendency to increase $p_{\pi}\text{-C-O}$ interactions.

From the analysis of the results, it can be concluded that hyperconjugative stabilization is a likely factor in non-planarity.

The question of whether $\sigma\text{-bond}\text{-}\sigma\text{-bond}$ repulsions or $p_{\pi}\text{-}\sigma\text{-allylic}$ bond stabilizations, are the more responsible (if they are so) for the olefinic hydrogen bending cannot be answered *a priori*: only actual calculations in which the effects of the two kinds of interaction can be compared are able to distinguish between them and to establish which factor is dominant in the various cases. Houk and co-workers^{3c,d} argued that $\sigma\text{-}\pi$ effects can be shown to be part of the torsional effect by describing the double bond in terms of localized bent bonds. They also stated that $\sigma\text{-}\pi$ hyperconjugation and torsional repulsions have the same geometrical dependence and, although conceptually separable, are theoretically and experimentally indistinguishable. We feel, however, that our approach (see below) is able to distinguish between these two types of interactions. In the following section this problem is approached quantitatively.

Analysis of the effects of intramolecular interactions

The model introduced here is described in detail in the Appendix and is based on the use of a hybrid atomic orbital approach for the calculation of the total energy of the molecule. Hybridization defines an atomic orbital basis whose elements show the best localization on single σ -bonds, π -bonds, lone pairs, etc. yet retaining complete invariance; as a consequence, each off-diagonal term of the energy matrix representing the interaction between two elements of the basis represents also the interaction between the molecular fragments (bonds, lone pairs, etc.) to which these elements are assigned by the hybridization procedure. Accordingly, what we call a $\sigma\text{-}\sigma$ interaction arises from the energy matrix terms between the σ -elements of the atomic basis involved in the two σ -bonds, whereas a $\pi\text{-}\sigma$ interaction arises from elements assigned to a π -system and elements assigned to a σ -bond. It should be noted that the notations $\sigma\text{-}\sigma$ and $\pi\text{-}\sigma$, which are widely used for indicating the interactions between filled molecular orbitals, assume a different meaning in our model, and will be used throughout according to our definition.

The change in the molecular energy caused by the suppression of selected terms of the energy matrix, with respect to the calculation in which all the interactions are present, defines the effect of the selected interactions. Obviously, the calculated effect of the interactions depends also on the approximations of the procedure for the energy calculation; even if better approximations are considered in future work, we did find that C-INDO parametrization¹¹ is a reasonable choice for our problems.

The analysis was conducted on all the compounds under study and a large collection of significant results are reported in Tables 3–10 in order to show both the coherence and soundness of the procedure and the overall consistency of the answers regarding which intramolecular interactions are of paramount importance in the problem of cyclic alkene pyramidalization.

The results in Tables 3–10 refer to molecules in their optimum geometry and in their *anti* ($\alpha = -20^\circ$) and *syn*

Table 3. Analysis of intramolecular interactions for bicyclo[2.1.0]pentene (**1a**)^a

	$\alpha = 7.08^\circ$	$\alpha = -20^\circ$	$\alpha = +20^\circ$	$\Delta \pm 20$
NORM	0.0(ref.)	5.69	2.39	-3.29
$\sigma\text{-conj.}$	-158.69	-159.51	-159.51	-0.00
TSI	-36.25	-36.60	-40.06	-3.46
$\sigma\text{-}\sigma$	-18.78	-18.42	-19.40	-0.98
$\pi\text{-}\sigma$	-17.47	-18.19	-20.66	-2.48
$\pi\text{-C-C}$	-11.34	-9.05	-12.02	-2.97
$\pi\text{-C-H}$	-4.56	-3.95	-4.66	-0.71
$\pi\text{-bonds}$	-16.04	-13.11	-16.79	-3.68
$\pi\text{-CH}_2$	-0.59	-0.42	-0.66	-0.24

^a C-INDO calculations (total energies in kcal mol⁻¹) on *ab initio* optimized structure (4-31G) and on deformed (forced *syn* bent $\alpha = 20^\circ$ and forced *anti* bent $\alpha = -20^\circ$) model structures.

α = out-of-plane bending of the olefinic hydrogens.

$\Delta \pm 20 = E_{+20^\circ} - E_{-20^\circ}$

Table 4. Analysis of intramolecular interactions for norbornene (**5a**)^a

	$\alpha = -4.35^\circ$	$\alpha = -20^\circ$	$\alpha = +20^\circ$	$\Delta \pm 20$
NORM	0.0(ref.)	1.79	4.43	2.64
$\sigma\text{-conj.}$	-226.15	-226.67	-226.67	0.00
TSI	1.61	-0.96	1.72	2.68
$\sigma\text{-}\sigma$	28.00	27.71	28.01	0.30
$\pi\text{-}\sigma$	-26.39	-28.67	-26.29	2.38
$\pi\text{-C-C}_m$	-5.40	-4.43	-7.03	-2.60
$\pi\text{-C-C}_e$	-16.13	-17.29	-13.44	3.86
$\pi\text{-C-H}$	-1.65	-2.01	-0.99	1.02
$\pi\text{-bonds}$	-22.25	-22.77	-20.60	2.17
$\pi\text{-CH}_2\text{-m}$	-1.31	-1.10	-1.62	-0.52
$\pi\text{-CH}_2\text{-e}$	-2.82	-2.96	-2.39	0.57

^a C-INDO calculations on STO-3G structure.

($\alpha = +20^\circ$) deformed geometries; the comparison between the deformed molecules has the advantage of amplifying the energy effects of non-planarity and of showing that, even though pyramidalization appears to be small, the energetic asymmetry caused by

Table 5. Analysis of intramolecular interactions for 5,6-dioxanorbornene (**5c**)^a

	$\alpha = -5.14^\circ$	$\alpha = -20^\circ$	$\alpha = +20^\circ$	$\Delta \pm 20$
NORM	0.0(ref.)	3.77	6.71	2.94
σ -conj.	-378.03	-378.82	-378.90	-0.08
TSI	58.36	54.92	57.77	2.84
σ - σ	86.12	85.63	85.88	0.25
π - σ	-27.76	-30.70	-28.11	2.59
π -C-C _m	-7.48	-5.92	-9.71	-3.79
π -C-O	-19.28	-20.55	-15.59	4.95
π -C-H	-0.94	-1.30	-0.36	0.94
π -bonds	-25.72	-26.07	-23.43	2.64
π -lone pairs	-0.73	-0.61	-0.58	0.03
π -CH ₂	-1.14	-0.90	-1.47	-0.57

^aC-INDO calculations on STO-3G structure.

Table 6. Analysis of intramolecular interactions for 7-oxanorbornene (**5b**)^a

	$\alpha = -3.05^\circ$	$\alpha = -20^\circ$	$\alpha = +20^\circ$	$\Delta \pm 20$
NORM	0.0(ref.)	3.65	6.06	2.40
σ -conj.	-277.41	-278.31	-278.27	0.04
TSI	54.39	50.70	53.10	2.40
σ - σ	80.49	79.94	80.12	0.18
π - σ	-26.10	-29.24	-27.01	2.22
π -C-O	-5.82	-4.08	-8.06	-3.99
π -C-C _e	-16.59	-17.92	-13.75	4.17
π -C-H	-2.31	-2.88	-1.40	1.48
π -bonds	-23.46	-23.60	-22.07	1.51
π -lone pairs	-0.04	-0.00	-0.09	-0.07
π -CH ₂	-2.50	-2.67	-2.03	0.64

^aC-INDO calculations on STO-3G structure.

Table 7. Analysis of intramolecular interactions for oxabicyclo[2.1.0]pentene (**1b**)^a

	$\alpha = 7.29^\circ$	$\alpha = -20^\circ$	$\alpha = +20^\circ$	$\Delta \pm 20$
NORM	0.0(ref.)	5.11	2.55	-2.55
σ -conj.	-204.70	-205.68	-205.49	0.20
TSI	-2.16	-3.22	-5.50	-2.28
σ - σ	13.92	13.81	13.57	-0.24
π - σ	-16.07	-17.03	-19.06	-2.03
π -C-O	-12.03	-10.15	-12.35	-2.20
π -C-H	-2.79	-2.16	-2.95	-0.80
π -bonds	-15.60	-12.91	-16.06	-3.15
π -lone pairs	0.03	0.02	0.06	0.03

^aC-INDO calculations on 4-31G structure.

deformations forced towards the transition states is significant. The NORM row reports the results of conventional C-INDO calculations, and the other rows contain the differences between NORM energies and the energies obtained when subsets of intramolecular interactions are suppressed; according to the definition, these entries represent the effects, either negative, i.e. stabilizing, or positive, i.e. destabilizing, caused by those interactions. The figures in the last column in each table are the differences between the deformed molecules ($E_{+20^\circ} - E_{-20^\circ}$); they represent the energetic

Table 8. Analysis of intramolecular interaction for bicyclo[2.2.0]hexene (**2a**)^a

	$\alpha = 3.91^\circ$	$\alpha = -20^\circ$	$\alpha = +20^\circ$	$\Delta \pm 20$
NORM	0.0(ref.)	6.12	2.81	-3.31
σ -conj.	-191.60	-192.52	-192.52	-0.00
TSI	11.10	10.38	6.98	-3.39
σ - σ	35.99	35.91	35.63	-0.29
π - σ	-24.89	-25.54	-28.64	-3.11
π -C-C	-14.93	-12.83	-15.61	-2.78
π -C-H	-8.60	-7.78	-8.69	-0.91
π -bonds	-23.02	-20.15	-23.72	-3.57

^aC-INDO calculations on 4-31G structure.

Table 9. Analysis of intramolecular interactions for dioxabicyclo[2.2.0]hexene (**2b**)^a

	$\alpha = 3.76^\circ$	$\alpha = -20^\circ$	$\alpha = +20^\circ$	$\Delta \pm 20$
NORM	0.0(ref.)	5.20	3.57	-1.64
σ -conj.	-349.64	-350.64	-350.52	0.12
TSI	57.53	55.66	54.29	-1.36
σ - σ	85.58	85.21	85.25	0.05
π - σ	-28.05	-29.55	-30.96	-1.41
π -C-O	-19.80	-18.88	-19.37	-0.49
π -C-H	-7.94	-7.00	-8.11	-1.11
π -bonds	-27.41	-25.54	-27.15	-1.61
π -lone pairs	-0.51	-0.30	-0.62	-0.32

^aC-INDO calculations on 4-31G structure.

Table 10. Analysis of intramolecular interactions for 3,4-dimethoxycyclobutene (**4d**)^a

	$\alpha = -1.43^\circ$	$\alpha = -20^\circ$	$\alpha = +20^\circ$	$\Delta \pm 20$
NORM	0.0(ref.)	3.08	4.47	1.39
σ -conj.	-373.85	-374.72	-374.61	0.11
TSI	128.90	125.84	127.52	1.69
σ - σ	156.18	155.76	156.07	0.31
π - σ	-27.28	-29.93	-28.55	1.38
π -C-O	-12.99	-13.38	-11.78	1.60
π -C-H	-13.31	-12.94	-12.85	0.10
π -bonds	-26.34	-26.32	-24.65	1.67

^aC-INDO calculations on 4-31G structure.

asymmetry (NORM row) and the asymmetry explained (or caused) by the various subsets of interactions (other rows).

Table 3 will be described in detail in order to clarify the above definitions.

Bicyclo[2.1.0]pentene shows a significant *syn* bending in its optimum geometry ($\alpha = +7.08^\circ$); accordingly, a $+20^\circ$ *syn* deformation is less expensive, by $-3.29 \text{ kcal mol}^{-1}$, than the corresponding -20° *anti* deformation. σ -Conjugation, due to through σ -bond interaction (TBI) (see Appendix A for definition), introduces a high stabilization in all the forms (about $-160 \text{ kcal mol}^{-1}$), but does not contribute at all to deformation asymmetry ($\Delta \pm 20$), which, on the other hand, appears to be caused exclusively by through-space interaction (TSI). These interactions, even though weaker than TBI, introduce a higher stabilization into the $+20^\circ$ than into the -20° form, and explain all of the asymmetry.

Now, TSI in our molecules can be classified either as σ - σ or π - σ interactions; the effects of π - σ interactions are found by zeroing the corresponding terms of the energy matrix, whereas the effects of σ - σ interactions are evaluated by difference.

One can see that π - σ interactions are largely responsible for the asymmetry. This conclusion also appears to hold for all the molecules under study together with the generalization that π - σ interactions, in our definition and C-INDO evaluation, always confer stabilization. In contrast, σ - σ interactions have, in general, large destabilizing effects (bicyclo[2.1.0]pent-2-ene, **1a**, is a remarkable exception) and give much lower contribution to the asymmetry index, $\Delta \pm 20$. It should be emphasized that, although σ - σ interactions include the whole group of those interactions, in the comparison between the deformed molecules ($\pm 20^\circ$) the differences are limited to the direction of the olefinic CH bonds.

The analysis of π - σ interactions can be detailed further by considering separately (i.e. by zeroing separately) the interactions between the π -AOs on the olefinic carbons (C-1 and C-2) and the σ -AOs involved in the C-3-C-5, C-4-C-5, C-3-H and C-4-H bonds around the C-3 and C-4 centres. It has been found that this subset of π - σ interactions is the most effective in causing asymmetry via different stabilizations of the deformed molecules; it is gratifying that the effects of π -C-C and of π -C-H interactions, separately evaluated, reproduce the effects of the same interactions taken together (π -bonds), particularly when the differences $\Delta \pm 20$ are considered: this additive property of the effects confers significance to our analysis.

Finally, the interaction of the π -AOs with the σ -AOs involved in the methylene group (π -CH₂) has minor effects.

It is worth noticing that the stabilization of the *syn*

bent form in **1a** due to the interaction between the π -AOs and the C-C and C-H σ -AOs agrees with the pictorial description in Figure 4, where *syn* rotation increases the overlaps between the π -AOs and the C-C and C-H bonds.

The more complicated cases of norbornenes are equally well described: σ - σ interactions, which introduce large destabilizations, give minor contributions to the origin of $\Delta \pm 20$, whereas π - σ interactions appear to dominate the asymmetry. In norbornene, for example, the *anti* bending, with respect to the methano bridge, is favoured by π -C-C-e ($3.86 \text{ kcal mol}^{-1}$) and π -C-1-H ($1.02 \text{ kcal mol}^{-1}$) interactions (C-C-e representing C-1-C-6 and C-4-C-5 bonds of the ethano bridge) and opposed by π -C-C-m ($-2.60 \text{ kcal mol}^{-1}$) interactions (C-C-m representing C-1-C-7 and C-4-C-7 bonds). The effect of π -C-C-e is larger than that of π -C-C-m interactions as a consequence of the directions of the bonds. Once again these numerical conclusions agree with the explanation of Figure 4 in terms of stabilizing overlaps between π AOs and hybrid atomic orbitals involved in the σ -allylic bonds.

The results for oxanorbornenes (Tables 5 and 6), similarly to those of norbornene, allow some interesting comparisons. Oxanorbornene **5b** is slightly less *anti* bent than norbornene, whereas dioxanorbornene (**5c**) is slightly more *anti* bent, as can be seen both from the extent of non-planarity (α values) and from the deformation asymmetry ($\Delta \pm 20$). The finding that in **5b** and **5c** π -C-O interactions have larger effects than the corresponding π -C-C interactions in **5a** can easily explain the observed trend.

Our conclusions for norbornene are at first sight at variance with those of Spanget-Larsen and Gleiter.^{6d,e} On the basis of EH calculations, they concluded that a reduction in hyperconjugative interaction is the driving force behind the observed ground-state bending of norbornenes. In particular, *anti* bending in norbornene occurs in order to minimize destabilizing hyperconjugative interactions of π -MO with the part of MOs of the 'cyclopentane ribbon' associated with the methano bridge. In contrast, our calculations indicate that *anti* bending follows from the fact that the stabilizing hyperconjugative interactions with the monoatomic bridge are offset by those with the diatomic part of the 'cyclopentane ribbon.' However, for comparison with conclusions of other workers it is worth stressing again that the model we are considering is different from the PMO model where intramolecular interactions are defined as the interactions between filled and empty *molecular orbital* (σ - σ , σ - σ^* , π - σ , π - σ^* , etc); in our model the interactions arise between *atomic orbitals*, and their role is evaluated via the changes of the *total energy* of the molecule; in our model hyperconjugation induces stabilization, and pyramidalization occurs in order to increase the stability of the system.

Tables 7-9 show the results for oxabicyclo[2.1.0]pentene (**1b**), bicyclo[2.2.0]hexene (**2a**) and dioxabicyclo[2.2.0]hexene (**2b**). Here one can see, even in comparison with Table 3, that the effect of π -C-O interactions, while higher than the corresponding π -C-C interactions, does not increase the energy difference between the deformed ($\pm 20^\circ$) forms so that the *syn* bending of the hydrocarbon is not increased by oxygen substitution and much more in **2b** the major role in favouring *syn* bending is left to π -C-H interactions.

Table 10 reports the results for *cis*-3,4-dimethoxycyclobutene (**4b**); here again one can assign the origin of facial asymmetry to π - σ interactions; whereas π -C-O and π -C-H interactions have comparable values, the role of π -C-O in driving distortions is much greater. Consistently, in *cis*-3,4-dichlorocyclobutene (**4c**) (results not reported here) only π -C-Cl interactions, which are also larger than π -C-H interactions are responsible for *anti* bending.

Finally, the interactions between the π -AOs and the methylene groups, and also the interactions between the π -AOs and the oxygen lone pairs, produce small effects and do not contribute significantly to non-planarity.

We conclude that one of the leading factors that determine the geometry of cyclobutenes is the tendency to maximize the π -C-X interactions. Whether or not this also results in a significant effect on out-of-plane bending of olefinic hydrogens depends on how much bending is necessary to maximize π -C-X interactions and on how easily the molecule can accommodate such a bending without a relevant increase in geometrical strain and a decrease in π -bond energy. However, it is clear that further studies are warranted, aimed at a more precise definition of the relationship between the effect of the heteroatom and the character of the heteroatom itself (e.g. its electronegativity).

CONCLUSIONS

A relationship between non-planarity of the double bond moiety in *cis*-3,4-disubstituted cyclobutenes and the facial selectivity of their reactions with 1,3-dipoles clearly emerges from theoretical and experimental data. We suggest that non-planarity not only parallels but actually plays a relevant role in determining the facial selectivity observed.

As for the origin of non-planarity, we have shown that *cis*-3,4-disubstituted cyclobutenes are pyramidalized so as to maximize π - σ interactions between the π -atomic orbitals of the olefinic carbons and the σ -atomic orbitals involved in the allylic bonds. As a rule, the strength of these stabilizing π - σ interactions increases in the order π -C-H < π -C-C < π -C-O. Pyramidalization of norbornene, 7-oxanorbornene, 5,6-dioxanorbornene and 5,6-dioxabicyclo[2.2.2]oct-2-ene can be explained by the tendency to maximise π - σ interactions as well.

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APPENDIX. MODEL CALCULATIONS FOR THE ANALYSIS OF INTRAMOLECULAR INTERACTIONS

The present model is based on the definition of molecular subsystems (σ -bonds, π -systems, lone pairs, molecular fragments) to which each element of a convenient (hybrid) basis can be assigned. The hybrid basis is obtained by unitary transformation of a valence AO basis, according to the maximum localization criterion.¹² MO calculations are made in an NDO all-valence electron approximation, the C-INDO method. In a paper in which the C-INDO procedure was formulated,¹¹ the role of σ - σ , σ - π and π - π interactions in INDO quality conformational energies was investigated. Momicchioli *et al.*¹¹ showed that a proper balance of these interactions, introduced via empirical screening parameters, gives a good overall agreement between experimental or *ab initio* conformational energies and the INDO results. Difficulties still remain when conformations are strongly dependent on interactions involving lone pairs: in those cases the lack of directionality of two-centre repulsion integrals (taken as if they were spherical 2s orbitals) depresses σ - σ repulsions.

The requirement that MOs of a subsystem be the stationary states of a one-electron model is equivalent to the requirement that the energy matrix be factorized into blocks corresponding to the various subsystems into which the molecule is partitioned. The overlap matrix and the density matrix must also be factorized correspondingly. In fact, the energy matrix of the hybrid basis is *not* block-factorized: a number of inter-block elements introduce inter-subsystem interactions clearly recognizable in the corresponding elements of the density matrix.

Two kinds of inter-block elements can be distinguished in the energy matrix. Off-diagonal *one-centre* terms, not present in the overlap matrix because of orthogonality, follow from the differences between the valence states ionization energies (1s and 1p) of the s and p AOs and are usually large.

$${}^A H_{i,j}^{\text{core}} = a_i a_j (1s - 1p); \quad {}^{A,B} H_{i,j} = \beta_{i,j}^{\circ} S_{i,j}$$

Their value depends on the coefficients a_i and a_j of 2s AO in the hybrids h_i and h_j , on the same atom A, and becomes zero when one or both h s are pure p AOs. It follows that off-diagonal one-centre terms, relative to σ - π and π - π interactions, are zero, whereas they are large and introduce large delocalizations in σ -systems (σ -conjugation). The relevance of these terms and their chemical implications have been discussed by Dewar.¹³

Off-diagonal *two-centre* terms between basis elements of different subsystems are proportional to their overlap integrals and cause through-space interactions (TSI) between the subsystems: according to the assignment of the basis elements to σ , π or lone pair sub-system, these interactions can be called σ - σ , σ - π , π -lone pair etc., interactions.

Following this scheme, an analysis of intramolecular interactions can be made by calculating the change in total energy caused by the suppression of selected off-diagonal elements of the complete energy matrix; the requirement for a meaningful calculation is that the corresponding elements of the resulting density matrix vanish. This last condition may exclude the analysis of single interactions but, once fulfilled, it guarantees that the suppressed interactions are independent of those left in the calculation.

Suppression of all the off-diagonal terms, except those corresponding to σ - and π -bonds, produces a localized description of the molecule: the density matrix is strictly localized and the energy difference from a 'normal' calculation, where all the interactions are present, corresponds to the full localization energy.

A calculation where all TSI overlap interactions are suppressed provides a density matrix in which all of the corresponding two-centre terms are negligible, so that the energy difference can be taken as the effect of TSI interactions on the stability of the molecule; as this calculation contains one-centre off-diagonal interactions, σ -conjugation, i.e. through- σ -bond conjugation, can be obtained as the difference between the energy of this calculation and the energy of the σ -localized description.

The π - σ subset of TSI appears to be reasonably independent of the other overlap interactions (i.e. σ - σ) and the same happens to various subsets of π - σ interactions. This feature allows some detail in the analysis of intramolecular interactions, i.e. the separate analysis of small groups of π - σ interactions.

The above procedure, tested on the classical problems of the rotational barrier of ethane and of the chair-boat barrier of bicyclo[3.2.0]hept-6-enes,¹⁰ gives simple explanations in perfect agreement with the qualitative bond-bond repulsion model depicted in the relative Newman projections.¹⁴

Studies are in progress towards an *ab initio* version of the above analysis.

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