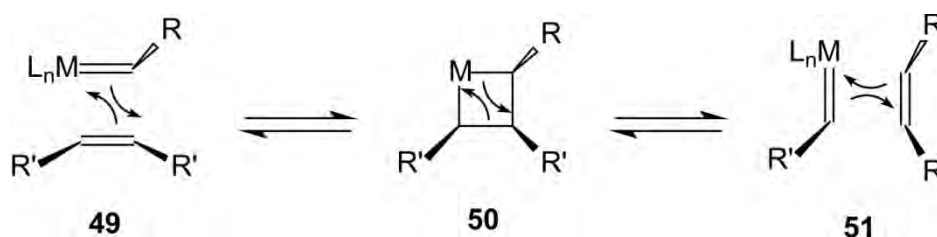


3. Molecular Modelling Study

3.1 Introduction

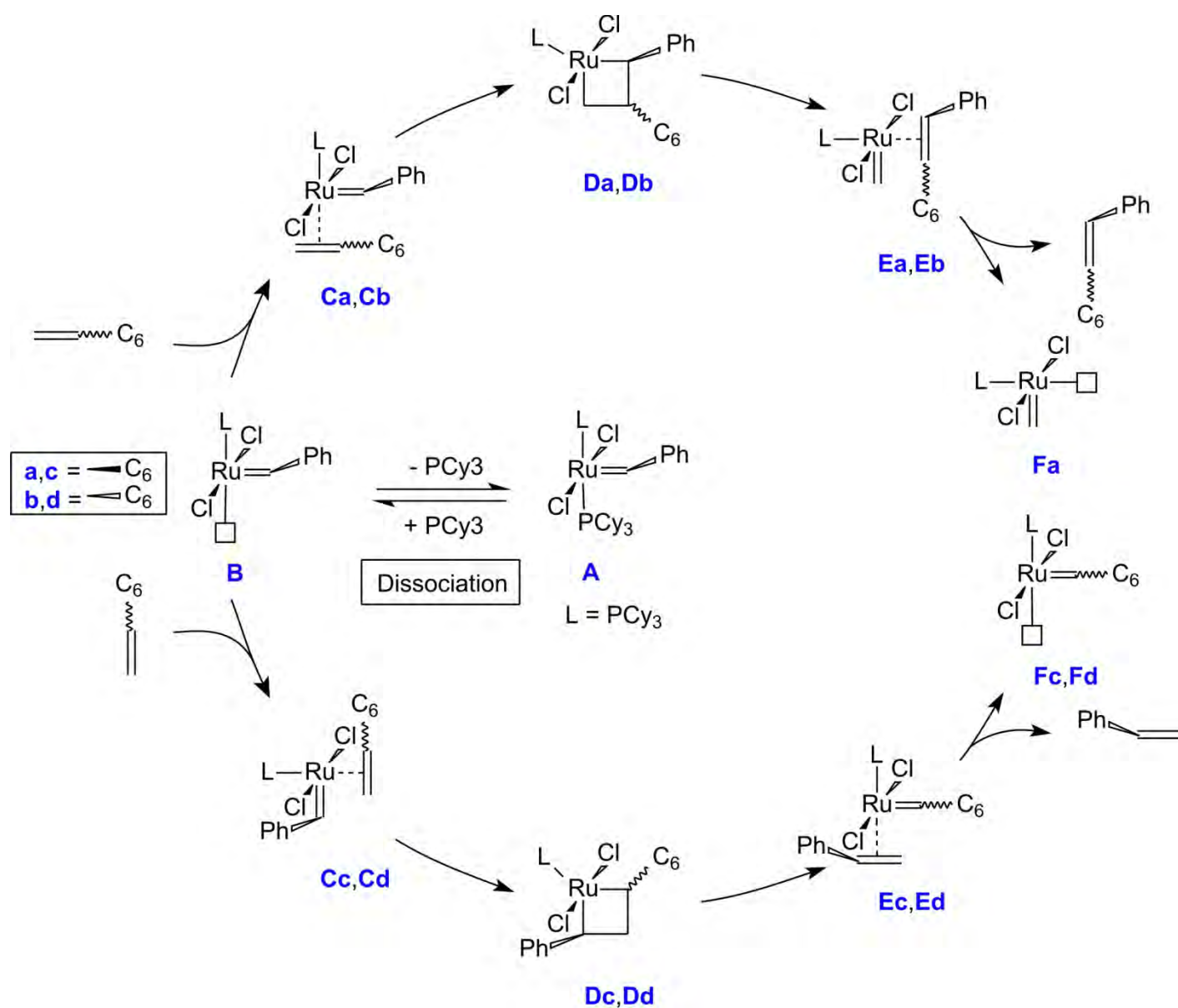
As already mentioned in **Chapter 2**, the commonly accepted mechanism for the alkene metathesis reaction was proposed by Chauvin.^{1,2} It includes, among other things, a [2 + 2]-cycloaddition between a transition metal alkylidene complex and the alkene to form a metallacyclobutane ring (**Scheme 3.1**). A cycloreversion takes place to yield a new alkylidene and a new alkene. If the reaction is repeated enough times, an equilibrium mixture of alkenes will be obtained.^{1,2}



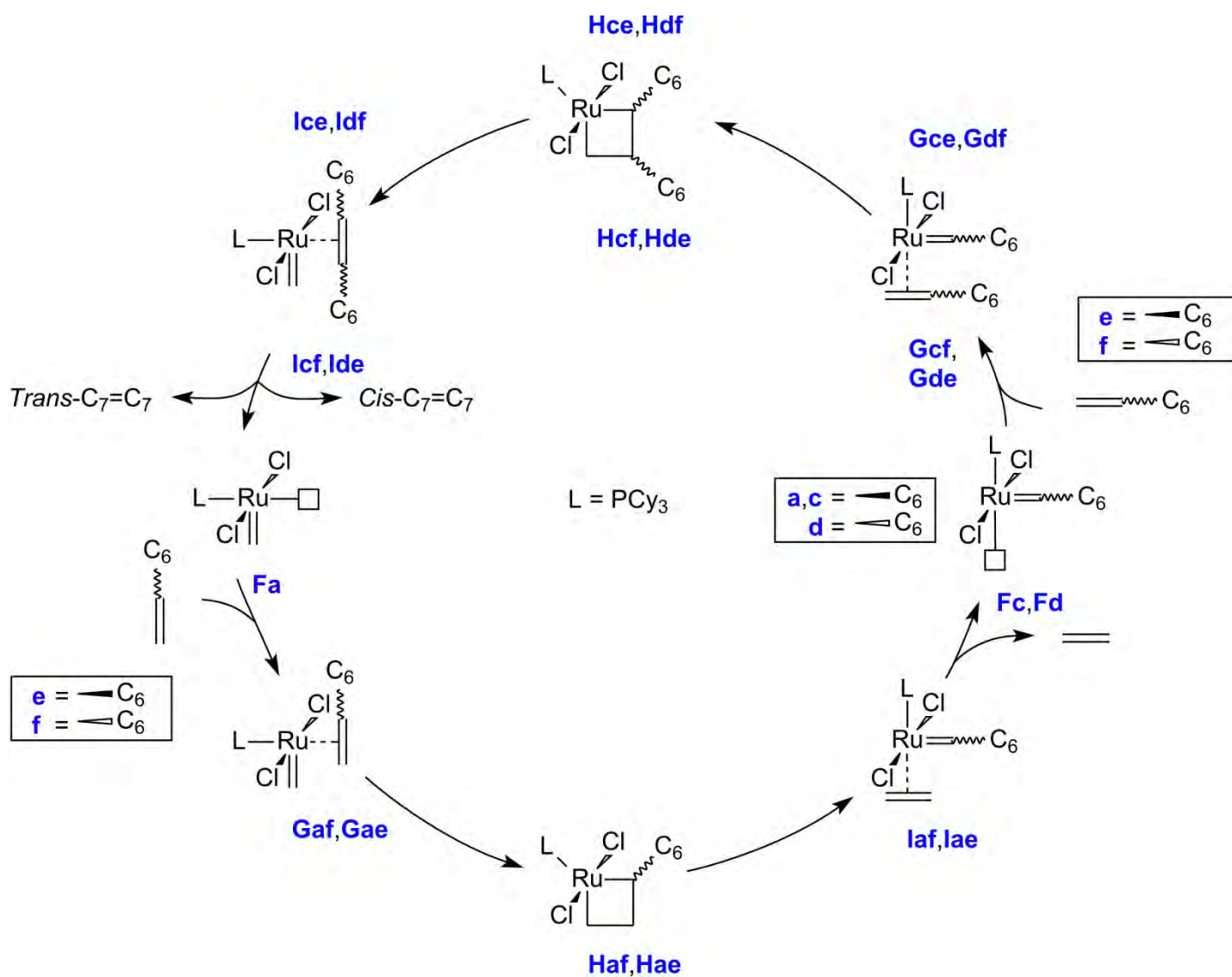
Scheme 3.1 A [2 + 2]-cycloaddition between a transition metal alkylidene complex and the alkene.

Theoretical studies are very useful to resolve the effect of ligand coordination and to gain a deeper insight into the mechanism of the catalytic reaction. Several publications have appeared wherein mechanistic parameters were calculated or experimental work was combined with theoretical studies of the alkene metathesis mechanism with ruthenium carbenes.³⁻¹³ In these studies, the catalytic cycle and ligand dissociation of the methyldiene species $RuCl_2(PR_3)_2(=CH_2)$ (**Fa**) were thoroughly investigated (**Scheme 3.2** and **Scheme 3.3**). In many of these studies, model ligands $[PR_3$ ($R = H, Me$)] and/or ethene as a model substrate were used, with the methyldiene complex **Fa** to lower the calculation costs. This leaves room for interpretation about the steric and electronic influence of the actual ligands (PCy_3 versus PR_3 , ($R = H, Me$)) and substrates (1-octene versus ethene) with the benzyldiene complex (versus the methyldiene complex) as precatalyst.^{14,15}

Jordaan *et al.*^{14,15} reported the first complete molecular modelling study without any simplification of the dissociation step (**A** to **B**), activation steps (**B** to **Fa/Fc/Fd**) and catalytic cycles (**Fa** to **Fc/Fd** or **Fc/Fd** to **Fa**) with Grubbs 1 (**A1**). The catalytic cycles investigated by Jordaan *et al.*^{14,15} are illustrated in **Schemes 3.2** and **3.3**. In **Schemes 3.2** and **3.3**, the capital letters indicate time and again the current step in the mechanism, while the lower case letters indicate the orientation of the alkene chain (in the plane (**b**, **d** and **f**) or out of the plane (**a**, **c** and **e**) of the paper) coordinated to



Scheme 3.2 The dissociation (**A** to **B**) and activation steps (**B** to **F**) during the productive metathesis of 1-octene with $\text{RuCl}_2(\text{PCy}_3)_2\text{L}(=\text{CHPh})$ ($\text{L} = \text{PCy}_3$).^{14,15}



Scheme 3.3 The catalytic cycles during productive metathesis of 1-octene with $\text{RuCl}_2(\text{PCy}_3)_2\text{L}(=\text{CHPh})$ ($\text{L} = \text{PCy}_3$).^{14,15}

the catalyst. In **Scheme 3.3**, the double lower case letter indicates the orientation of the two different alkene chains that are coordinated to the catalyst at that time.

Adlhart *et al.*⁴ proposed several mechanistic routes that can be divided into two main categories: an associative and a dissociative mechanism. Studies have shown that the dissociative mechanism, initiated by the dissociation of a phosphine ligand from $\text{RuX}_2(\text{PR}_3)_2(=\text{CHR}')$ to yield a 14-electron species, is preferred.^{3,4,16} Chen *et al.*⁵ confirmed this 14-electron species by identifying it by means of gas phase ESI-MS/MS. Sanford *et al.*³ investigated the rate of phosphine dissociation and initiation of the alkene metathesis reaction with $\text{RuX}_2(\text{PR}_3)_2\text{L}(=\text{CHR}')$ -type precatalysts theoretically and experimentally.

Although many aspects of the alkene metathesis mechanism in the presence of **A1** were elucidated with various techniques, including kinetic measurements, there are still aspects that have to be investigated.^{17,18} These include the determination of the most active species during the metathesis reaction, as well as elucidation of the mechanism when the benzylidene, and not the methyldiene, is used as the precatalyst.^{17,18} A conceptual model of the complete mechanism of the productive, dissociative mechanism of the metathesis reaction of 1-octene in the presence of **A1** has been published.^{14,15} The results generated during this study will be discussed according to this model.

3.2 Hardware

A cluster with 336 CPUs was used for all molecular modelling investigations¹⁹:

1 x Master node	HP BL460C G6 - 2 Quad Core 2.93 GHz, 16GB RAM, 2 x 146 GB HDD
12 x Compute nodes	HP BL460C G6 - 2 Quad Core 2.93 GHz, 16GB RAM, 2 x 146 GB HDD, ProLiant BL2x220c G5, HP BL460C G1
1 x HP EVA 4400 SAN 3TB	
1 x Storage server	HP BL460C G6
Operating system	Scientific Linux SL release 5.3
Cluster operating system	Rocks 5.2 - Scientific Linux SL release 5.3

3.3 Calculation methods

3.3.1 Geometry optimisations

All calculations were performed with the DMol³ density functional theory DFT code^{20,21,22} as implemented in Accelrys Materials Studio[®] 5.0. The quantum-chemical calculations were carried out by DFT, since it usually gives realistic geometries, relative energies and vibrational frequencies

for transition metal compounds. The non-local generalised gradient approximation (GGA) functional by Perdew and Wang (PW91) was used for all geometry optimisations.²³ The convergence criteria for these optimisations consisted of threshold values of 2×10^{-5} Ha, 0.004 Ha/Å and 0.005 Å for energy, gradient and displacement convergence, respectively, while a self-consistent field (SCF) density convergence threshold value of 1×10^{-5} Ha was specified. The spin was set on restricted. For spin restricted wave-functions, the same orbitals are used for the alpha and beta electrons. DMol³ utilises a basis set of numeric atomic functions, which are exact solutions to the Kohn-Sham equations for the atom.²⁴ These basis sets are generally more complete than a comparable set of linearly independent Gaussian functions and have been demonstrated to have small basis set superposition errors.²⁴ In this study, a polarised split valence basis set, termed double numeric polarised (DNP), was used. All geometry optimisations employed highly efficient delocalised internal coordinates.²⁵ The use of delocalised coordinates significantly reduces the number of geometry optimisation iterations needed to optimise larger molecules compared to the use of traditional Cartesian coordinates.

The optimisation process consists of two steps²⁶:

1. Energy evaluation

The energy term [The coordinates of a structure combined with a force field form the energy term (or target function). The energy term is the equation that describes the potential energy surface of a certain structure as a function of its atom coordinates.] has to be defined and evaluated for a certain conformation. Energy terms that include external restriction terms to evaluate the optimisation can be defined in additional energy terms.

2. Conformer adjustment

The conformation is adjusted to lower the value of the energy term. A minimum can be obtained after one adjustment or may need thousands of iterations, depending on the nature of the algorithm, the form of the energy term and the size of the structure.

The effectiveness of the optimisation is determined by evaluating both the time needed to evaluate the energy term and the number of adjustments (iterations) needed to converge to a minimum.

DMol³ is a DFT quantum mechanical code that is used to investigate problems in the gas, solvent and solid state.²⁶ The generalised gradient approximation (GGA) functional of Perdew and Wang²³ (PW91) is derived by evaluating low and high density systems and applying various addition rules.

A greater freedom of variation is achieved by providing bigger basis sets. A complete second set of functions is obtained by doubling the basis set size; this is called a double numeric (DN) set. For the first row of atoms, reasonable double basis set functions are obtained for the +2 ions.²⁶ A good polarisation function for each of the atoms is obtained for a hydrogen-type three-dimensional orbital of $Z = 5$. A hydrogen-type 2p function, for $Z = 1.3$, is used for hydrogen. The use of several

core charges to generate polarisation functions correlates with the variation of zeta when Gauss-type basis sets are used. For metals 4p, polarisation functions are generated by solving the atom equations for the $4s \rightarrow 4p$ excited states.²⁶ Basis set quality was analysed in depth by Delly.²⁰ **Table 3.1** describes the basis sets used by DMol³ in Accelrys Materials Studio[®] 5.0.

Table 3.1 The basis sets used by DMol³ in Accelrys Materials Studio[®] 5.0²⁶

Basis set	Description	Examples
MIN	Minimal Basis. One AO for every occupied atom orbital. Provides low accuracy, but fast calculations.	H: 1s C: 1s 2s 2p Si: 1s 2s 2p 3s 3p
DN	Double numeric. MIN plus a second set valence AO's. Improved accuracy over MIN.	H: 1s 1s' C: 1s 2s 2p 2s' 2p' Si: 1s 2s 2p 3s 3p 3s' 3p'
DND	Double numeric plus d-functions. Like DN with polarised d-functions on all non-hydrogen atoms. This basis set provides reasonable accuracy for moderate calculation costs.	H: 1s 1s' C: 1s 2s 2p 2s' 2p' 3d Si: 1s 2s 2p 3s 3p 3s' 3p' 3d
DNP	Double numeric plus polarisation. Like DND with a polarisation p-function on all hydrogen atoms. Best accuracy, highest costs. Important for hydrogen bonding.	H: 1s 1s' 1p C: 1s 2s 2p 2s' 2p' 3d Si: 1s 2s 2p 3s 3p 3s' 3p' 3d

3.3.2 Transition state search

All of the geometries optimised were also subjected to full frequency analyses at the same GGA/PW91/DNP level of theory to verify the nature of the stationary points. Equilibrium geometries were characterised by the absence of imaginary frequencies. Preliminary transition state (TS) geometries were obtained by the integrated linear synchronous transit/quadratic synchronous transit (LST/QST) algorithm available in Materials Studio[®] 5.0. These preliminary structures were then subjected to full TS optimisations using an eigenvector following algorithm.²⁶

All transition states were obtained with synchronous transition methods. By starting with the reagents and products, synchronous transition methods interpolate a reaction path to obtain a transition state. These methods vary the searches for an energy maximum with a restricted search for a minimum to better refine the transition state. To achieve the best results, the structures of the reagents and products were optimised before the transition path was generated.²⁶

The linear synchronous transit (LST) method performs a single interpolation to a maximum energy. The quadratic synchronous transit (QST) method varies searches for an energy maximum with restricted minimisations to refine the transition state. A complete LST/QST calculation starts by performing an LST optimisation calculation. The transition approximation obtained this way is used to perform a QST maximisation. Hereafter, a conjugated gradient minimisation is performed. The cycle is repeated until a stationary point is reached, or the maximum amount of QST steps is exhausted. This method is more accurate than most other methods.²⁶

3.3.3 Frequency calculations

Frequency calculations of all the preliminary transition states, reagents and products structures were performed on the same GGA/PW91/DNP level of theory. Before further refinement, most transition states showed more than one imaginary frequency. One of the imaginary frequencies corresponded with a possible transition state, since the movement of the atoms in the obtained frequency was in the reaction coordinate. These possible transition state structures were subjected to another round of frequency calculations, where after a TS optimisation calculation was performed along with a frequency calculation to determine whether they were true transition states.

At the end of a successful transition state calculation, a stationary point is available. It is difficult to prove that a stationary point is a transition state. To do this, a frequency calculation has to be performed. A true transition state has only one imaginary frequency whose normal mode corresponds with movement of the atoms in the reaction coordinate. All eigenvalues will be real. A structure with more than one imaginary frequency is not a true transition state.²⁶ In this study, all the transition states had only one imaginary frequency and all the reagents and products structures had none.

3.3.4 TS optimisations

When the TS optimisation task is used, DMol³ starts from a reasonable guess for the transition state and performs a Newton-Raphson search on the potential energy surface.²⁶ This uses techniques similar to a search for an energy minimum, but searches instead for an energy maximum along one normal mode. Because this method follows one of the Hessian eigenvectors to an energy maximum, the method is often referred to as 'eigenvector following' (EF).²⁶

There must be a Hessian associated with the model in order to perform transition state optimisation.²⁶ Before proceeding, a Hessian must be generated by requesting a frequency calculation on the starting geometry. The transition state setup will automatically detect whether or

not you have a Hessian, and it will not allow you to submit a transition state optimisation without one.²⁶

3.4 Modelling system and notations

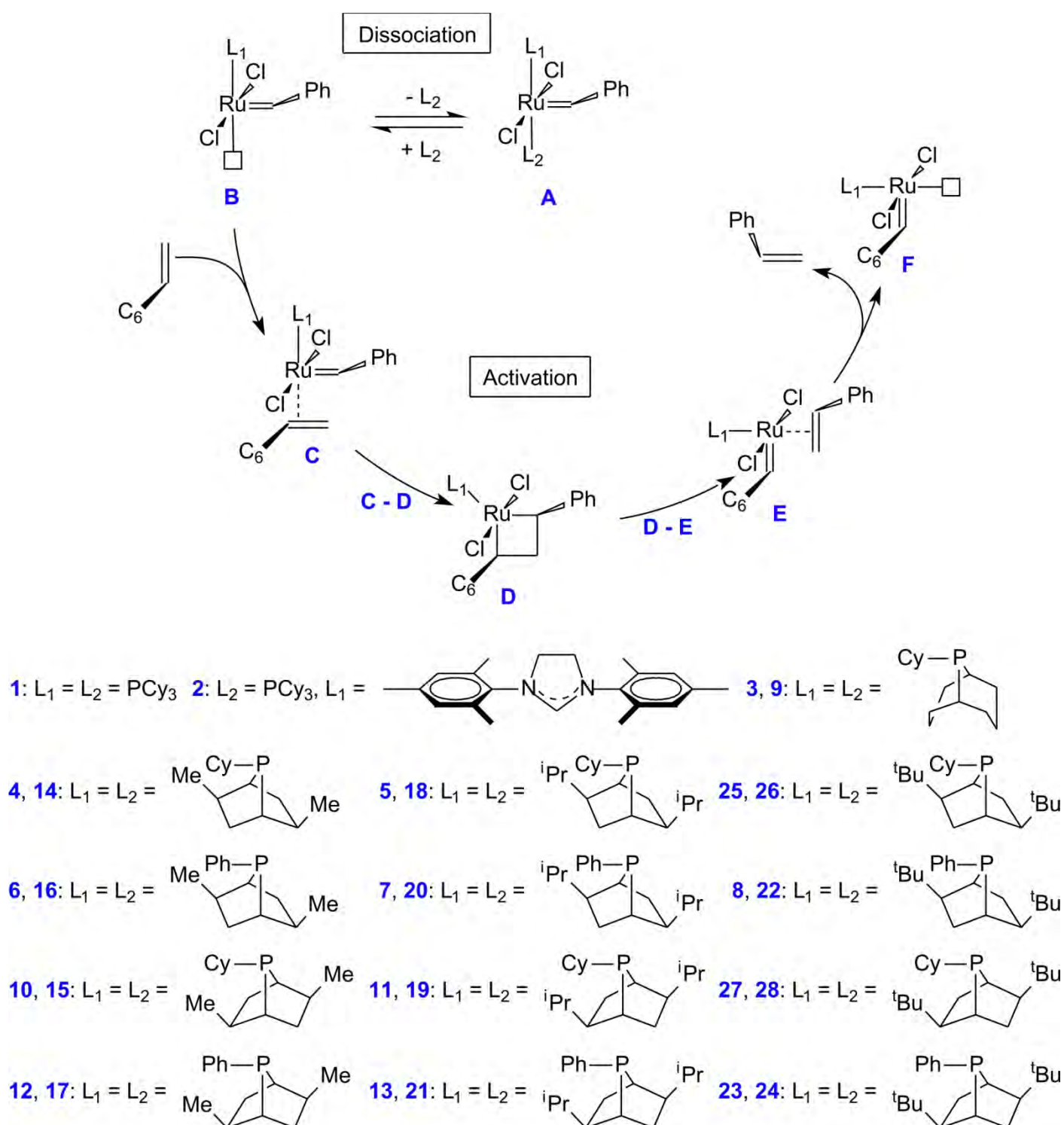
The productive metathesis of 1-octene to form *cis*- or *trans*-7-tetradecene in the presence of Grubbs-type carbene complexes is illustrated in **Schemes 3.4** and **3.5** (these schemes are based on **Schemes 3.2** and **3.3**, but are simplified to better illustrate the current investigation).

The mechanistic model is based on the mechanism proposed by Grubbs *et al.*^{3,16} and modelled by Adlhart and Chen⁴ and Jordaan *et al.*^{14,15} The symbols **A-N** are used for the different species in the reaction mechanism and the numerical suffix points to a specific precatalyst, for example **A1** points to the Grubbs 1 precatalyst (**Schemes 3.4** and **3.5**). Transition states could be determined for all the possible steps.

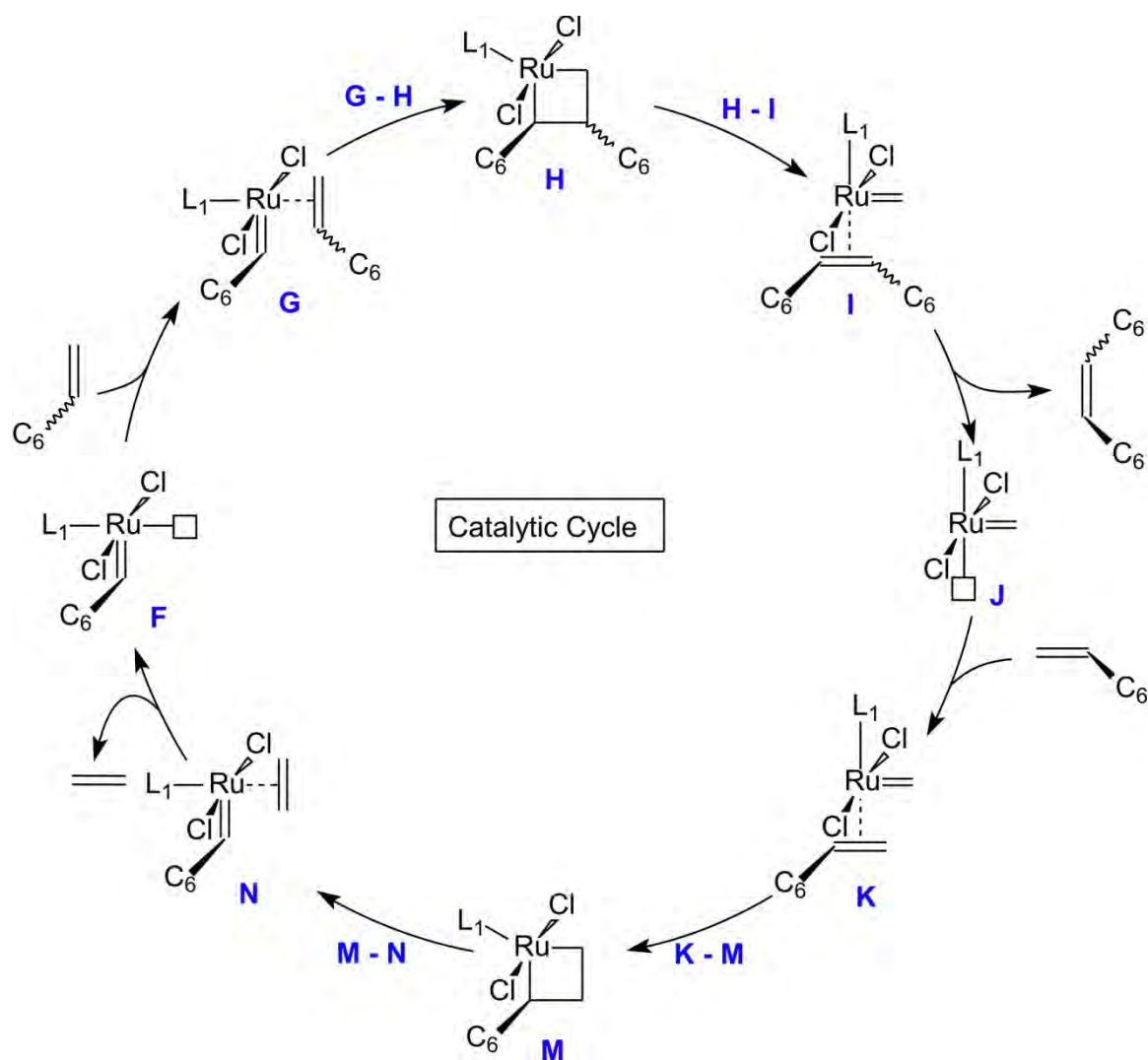
The mechanism starts with the dissociation of a phosphine ligand from the 16-electron species, **A**, to form the active 14-electron species, **B**. Hereafter, the activation steps, **B-F**, and the catalytic cycles, **F-N**, follow. The cycle consists of several formal [2 + 2]-cycloadditions to form a metallacyclobutane ring and cycloreversions to form the various catalytic active species.

The precatalyst must first go through an activation step, during which the catalyst is transformed from a benzylidene complex, **A**, to a heptylidene complex, **F**, before it can partake in the catalytic cycle. Activation takes place when 1-octene coordinates to the 14-electron intermediate, **B**, to form a π -complex, **C**, that undergoes a formal [2 + 2]-cycloaddition to form a metallacyclobutane ring, **D**, and reverts back to a π -complex, **E**. Release of the new alkene from the new π -complex leads to a catalytic active heptylidene species, **F**, which can partake in the catalytic cycle. Styrene is released to yield **F** wherein the alkylidene of the carbene points out of the plane of the paper.

During the catalytic cycle, the heptylidene is time and again converted to the methylidene, **J**, which is then converted back to the heptylidene, **F**, until all the 1-octene is used up or the catalyst is deactivated. During the conversion of the heptylidene to the methylidene, *cis*- or *trans*-7-tetradecene forms, while ethene forms when the methylidene is converted to the heptylidene. Although it is not indicated in the schemes, a mass balance was performed for the isolated system on all the results in the gas phase. For all the Gibbs-free energy values reported in this study, zero-point energy (ZPE) corrections in the gas phase, at 298.15 K and 1 atm, are included. Janse van Rensburg *et al.*¹³ reported that the relative Gibbs-free energies in the gas phase may not be directly correlated with the relative Gibbs-free energies in solution. They found that the gas phase values were still appropriate for relative comparison of the various catalyst systems.¹³



Scheme 3.4 The dissociation (A to B) and activation steps (B to F) during the productive metathesis of 1-octene with **A1** to **A28**.



Scheme 3.5 The catalytic cycle during productive metathesis of 1-octene with **A1** to **A28**.

3.5 Confirmation of calculation methods

To compare the different Grubbs-type precatalysts, it is helpful to gain some confidence in the calculation method by comparing the calculated bond lengths and angles of Grubbs 1 (**A1**), Grubbs 2 (**A2**) and Phobcat (**A3**) with the crystallographic data of Nguyen *et al.*²⁷ and Love *et al.*²⁸ and the calculated values of Jordaan *et al.*^{14,15} and Dwyer *et al.*²⁹ (**Table 3.2**).

Table 3.2 Crystallographic and theoretic values of essential bond lengths and angles of the Grubbs-type catalysts systems

Precatalyst	Bond lengths (Å)			Bond angles (°)		
	Ru=C	Ru-Cl _{ave}	Ru-P _{ave}	Cl-Ru-Cl	P(1)-Ru-P(2)	Ru=C-R
Grubbs 1 ²⁷ (A1)	1.838	2.390	2.416	168.21	161.90	136.70
Grubbs 1 ¹⁵ (A1)	1.878	2.452	2.490	160.97	163.35	136.04
Grubbs 1 ^a (A1)	1.878	2.456	2.485	163.95	163.02	136.43
Grubbs 2 ²⁸ (A2)	1.835	2.395	2.425 ^b	167.71	163.73	137.00
Grubbs 2 ²⁸ (A2)			2.085 ^{NHC}			
Grubbs 2 ¹⁵ (A2)	1.879	2.461	2.525 ^b	169.97	165.34	136.81
Grubbs 2 ¹⁵ (A2)			2.121 ^{NHC}			
Grubbs 2 ^a (A2)	1.876	2.458	2.528 ^b	169.83	166.00	136.75
Grubbs 2 ^a (A2)			2.124 ^{NHC}			
Phobcat ²⁹ (A3)	-	-	2.445	-	159.60	-
Phobcat ^a (A3)	1.880	2.453	2.441	167.39	159.50	136.87
Phct-indenylidene (A100) ³⁰	1.850	2.393	2.411	162.55	160.51	124.08

^a DMol³ GGA/PW91/DNP – full DFT-calculation of geometries.

^b The single Ru-phosphine bond length of **A2** is indicated.

^{NHC} The **A2** Ru-NHC bond length is indicated.

Jordaan *et al.*^{14,15} reported an acceptable correlation between the calculated bond lengths and angles when compared to the crystallographic data. From **Table 3.2**, it is clear that the newly calculated values for **A1**, **A2** and **A3** compare very well with those reported by Jordaan *et al.*^{14,15} and Dwyer *et al.*²⁹ Small discrepancies in the values can be attributed to small differences in the calculation method as well as differences in the versions of Accelrys Materials Studio[®] used.

Ideally, a comparison between the calculated values and the crystallographic data has to be done; however, until this data is available for the Phobcat precatalyst (**A3**), this comparison can unfortunately not be made. The only crystallographic data for the Phobcat precatalyst that could be found in literature was for the indenylidene derivative, **A100**, (**Figure 3.1**).³⁰ Although a comparison with the XRD data of this variant of the catalyst is not ideal, an idea of what the bond lengths and angles of **A3** might look like can be obtained. The obvious difference that can be seen between the XRD data of **A100** and the **A1** and **A2** benzylidenes is that the Ru=C bond length and the Ru=C-R angle of **A100** are shorter and smaller than that of **A1** and **A2**.

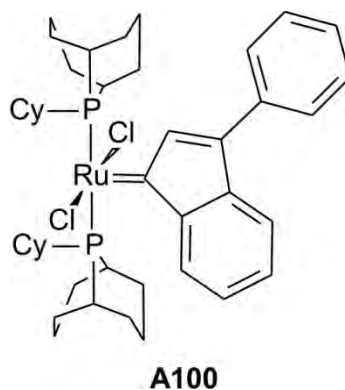


Figure 3.1 The Phobcat indenylidene precatalyst, **A100**.

In **Figures 3.2** and **3.3**, the calculated bond lengths and angles of Grubbs 1 (**A1**), Grubbs 2 (**A2**) and Phobcat (**A3** and **A9**) are compared with that of the new precatalysts **A4** to **A8** and **A10** to **A28** (**Table A1** in **Appendix A** contains all the numerical values). What can be seen from **Figure 3.2**, is that all the bond lengths are fairly similar. The average ruthenium-phosphine bond lengths show the biggest variation at 0.13 Å. The variations between the average ruthenium-chlorine bond lengths are not more than 0.07 Å. The carbene bond lengths vary by only 0.05 Å. The phenyl derivatives have shorter average Ru-P bond lengths than the cyclohexyl-derivatives.

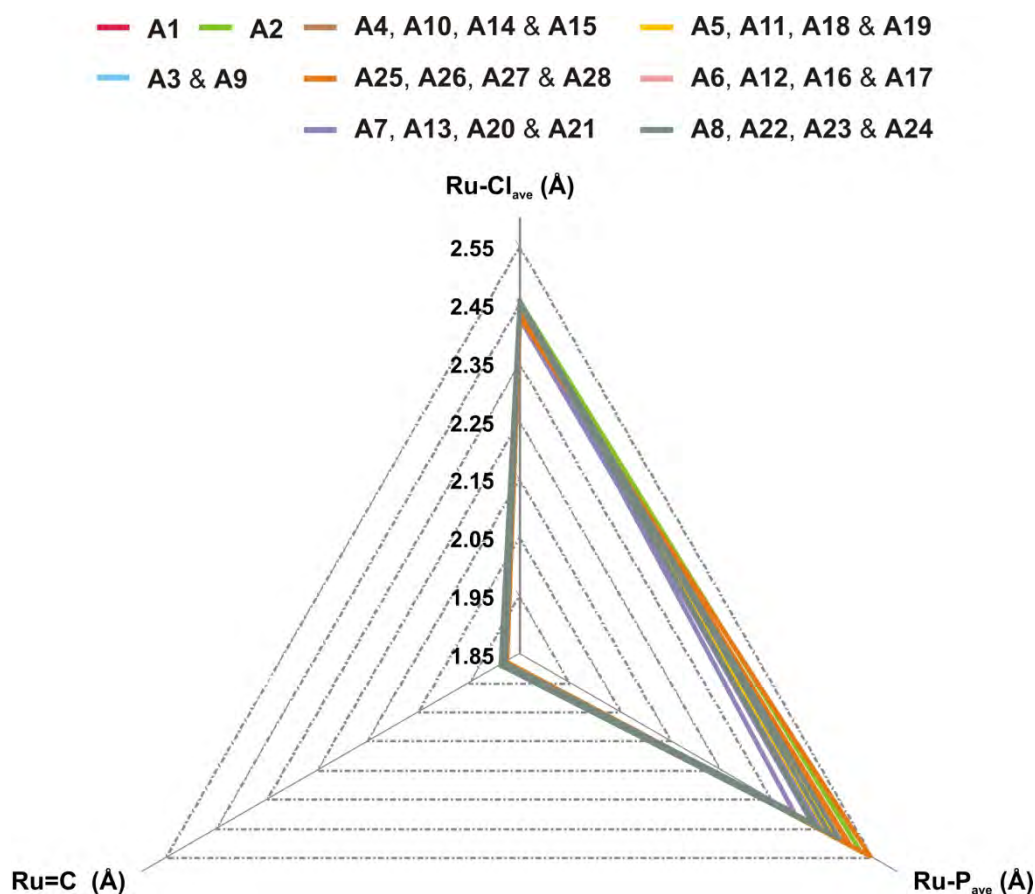


Figure 3.2 Calculated values of essential bond lengths of **A1** to **A28**.

From **Figure 3.3** it can be seen that the phosphorous-ruthenium-phosphorous [P(1)-Ru-P(2)] bond angles show the biggest variance at 20°. The chlorine-ruthenium-chlorine [Cl-Ru-Cl] bond angles vary by 14°. The Ru=carbene-benzylidene [Ru=C-R] angles show the smallest variance at a mere 4.79°. For the Cy ligands, a larger P(1)-Ru-P(2) angle corresponds with longer Ru-P bond lengths (the correlation coefficient has a value of 0.95-0.99). The opposite seems to be true for the Ph ligands, with a larger P(1)-Ru-P(2) angle corresponding with shorter Ru-P bond lengths (the correlation coefficient has a value of 0.96). Currently, there is no clear evidence in literature to correlate any bond length or angle variance with catalytic activity.

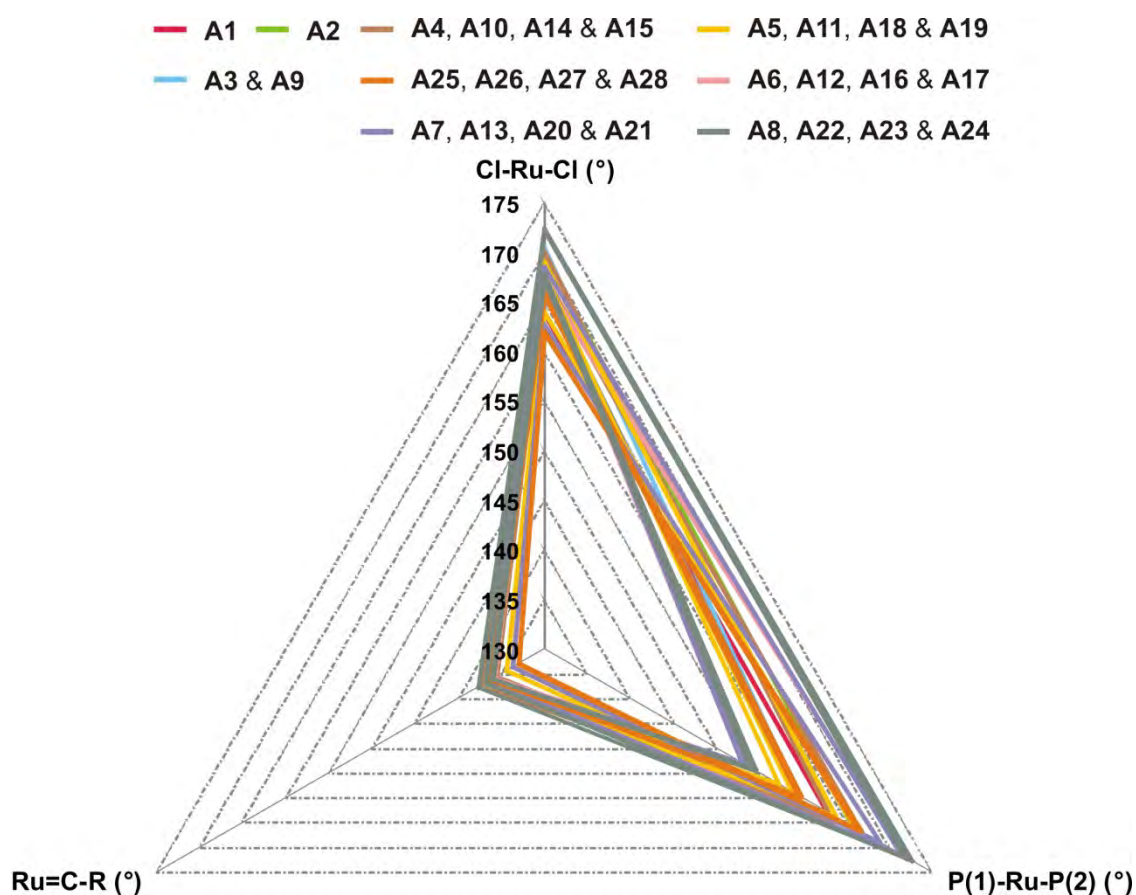


Figure 3.3 Calculated values of essential bond angles of **A1** to **A28**.

A final confirmation of the calculation method can be done by looking at the reported absolute phosphine dissociation energies of Torker *et al.*³¹ obtained by ESI-MS gas-phase experiments for **A1** and **A2** (**Table 3.3**). Since all the calculations in this study were done in the gas phase, it is worthwhile to compare the calculated values with those obtained experimentally. From **Table 3.3**, it is clear that the calculated values in this study compare well with those obtained experimentally. This is a significant result since it proves that the functional (GGA/PW91) and basis set (DNP) used in this study is of sufficient quality to provide reliable correlations with experimental results. In a 2009 study, Minenkov *et al.*³² tested the M06L density functional of Zaho and Truhlar³³ and came

to the conclusion that at 0 K it gives good correlation with the experimentally determined phosphine dissociation energies.

Table 3.3 Comparison of experimental ESI-MS measured and calculated dissociation energy values

Precatalyst	ΔE_e Torker ³¹ kJ.mol ⁻¹	ΔE_e Calculated ^a kJ.mol ⁻¹	ΔE_e Minenkov ³² kJ.mol ⁻¹
Grubbs 1 (A1)	139.75 ± 9.62	132.94	143.09
Grubbs 2 (A2)	154.39 ± 9.62	162.71	159.83

^a At 298.15 K zero-point energy corrections in the gas-phase included.

Du Toit³⁴ already performed a statistical analysis to determine the reliability of the various functionals in the Materials Studio DMol³ program. She determined that the GGA/PW91/DNP functional/basis set combination provided the most reliable data of the functionals investigated.³⁴ It is therefore extremely important to evaluate the validity of a calculation method beforehand, as was done here, before any attempt can be made to investigate the mechanism.

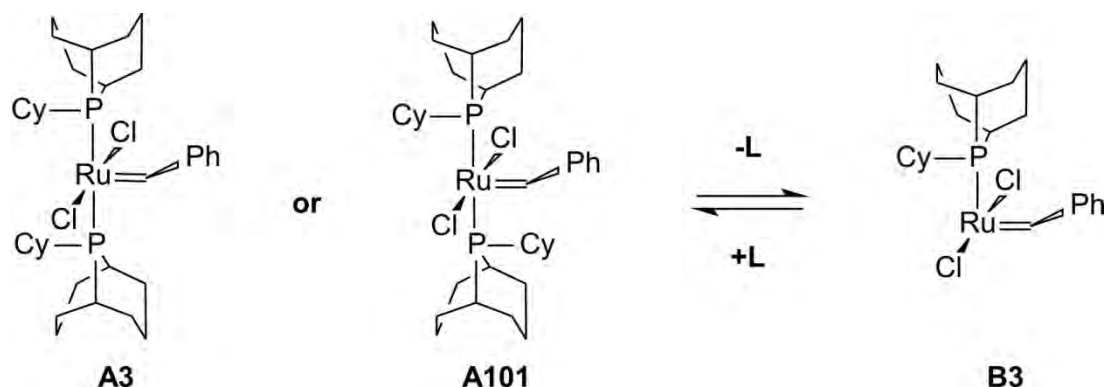
With the method validation done, the individual phases and steps of the mechanism will be discussed in more detail in the subsequent sections under the following headings:

- Initiation step,
- Activation steps,
- Catalytic cycle.

3.6 Initiation step

The accepted initiation step for the RuX₂(PR₃)L(=CHR')-catalyst systems takes place when one of the phosphine ligands dissociates from the precatalyst to yield the 14-electron species.^{3,4,16} The possibility of rotational conformers was reported by Dwyer *et al.*²⁹ for the Phobcat (**A3**) precatalyst. It was found in a molecular modelling study that the importance of the rotational conformers is not necessarily that significant.³⁵ Dissociation of a phosphine ligand from **A101** (wherein one Cy ring is *cisoid* and one Cy ring is *transoid* with regard to the Ph ring of the benzylidene) yields a catalytic active species (**B**) that correlates with either the dissociation step of the *cis-cis* (both Cy rings *cisoid* with regard to the Ph ring of the benzylidene) or the *trans-trans* (both Cy rings *transoid* with regard to the Ph ring of the benzylidene) conformer (**Scheme 3.6**). The energy difference between all the different steps in the complete catalytic cycle will only be the energy difference between the initial rotational conformers.³⁵ In this study, only *cis-cis* or *trans-trans* conformers will be considered; no *cis-trans* isomers were investigated. The current complete catalytic cycles took more than 6 000 calculations to obtain accurate values for all the steps investigated. It was felt that doing these additional calculations on the range of possible *cis-trans* isomers of the new

precatalyst was not necessary since the only information that would be obtained is confirmation that these conformers can form during the synthesis of the precatalysts.



Scheme 3.6 Dissociation of a phosphine ligand from different rotational conformers to yield an identical 14-electron active species, **B3**.

The energy difference between the various rotational isomers investigated for precatalysts **A3** to **A28** is summarised in **Table 3.4** (Cy and Ph indicate the Q-functional group and Me, iP and tB indicate the R-functional group). In **Table 3.4**, an 'a' or 'b' is assigned to differentiate between the possible rotational isomers of precatalysts **A4** to **A8** and **A10** to **A28**. **Figure 3.4** illustrates this difference in the R-group position on the backbone to differentiate between the 'a' or 'b' precatalysts and the orientation of the Q-group is used to differentiate between the *trans-trans* and *cis-cis* isomers.

Table 3.4 The energy difference between the various geometry optimised rotational isomers of **A4** to **A8** and **A10** to **A28**

	<i>Cis-cis</i> (a) kJ.mol ⁻¹	<i>Trans-trans</i> (a) kJ.mol ⁻¹	<i>Cis-cis</i> (b) kJ.mol ⁻¹	<i>Trans-trans</i> (b) kJ.mol ⁻¹
Phobcat	9.18 (A9)	0.00 (A3)		
CyMe	4.12 (A14)	2.03 (A4)	0.00 (A10)	4.03 (A15)
PhMe	12.09 (A16)	0.00 (A6)	10.59 (A12)	5.80 (A17)
CyiP	3.89 (A18)	9.51 (A5)	0.00 (A11)	7.49 (A19)
PhiP	8.31 (A20)	9.35 (A7)	15.07 (A13)	0.00 (A21)
CytB	9.84 (A26)	4.54 (A25)	13.16 (A28)	0.00 (A27)
PhtB	29.76 (A22)	2.06 (A8)	29.07 (A24)	0.00 (A23)

What becomes apparent from **Table 3.4** is that there is a variance in the energy difference between the various rotational isomers. Dwyer *et al.*²⁹ reported that the isomer with the lowest energy will be the most stable in the crystal form. The lowest energy isomer was set to zero according to this rationale. For most of the precatalysts it is one of the *trans-trans* isomers, the only exceptions are the **CyMe** and **CyiP** precatalysts. The small energy difference, in most cases, between the rotational isomers indicates that all of them will form when these catalysts are

synthesised. The larger energy difference between the **PhtB** precatalysts isomers, where the *cis-cis* isomers are a lot less stable than the *trans-trans* isomers, might be an indication that the *cis-cis* isomers will form to a lesser extent. The ratio of isomer formation has to be determined experimentally before the calculated results can be used in the future to try to predict an expected ratio of formation.

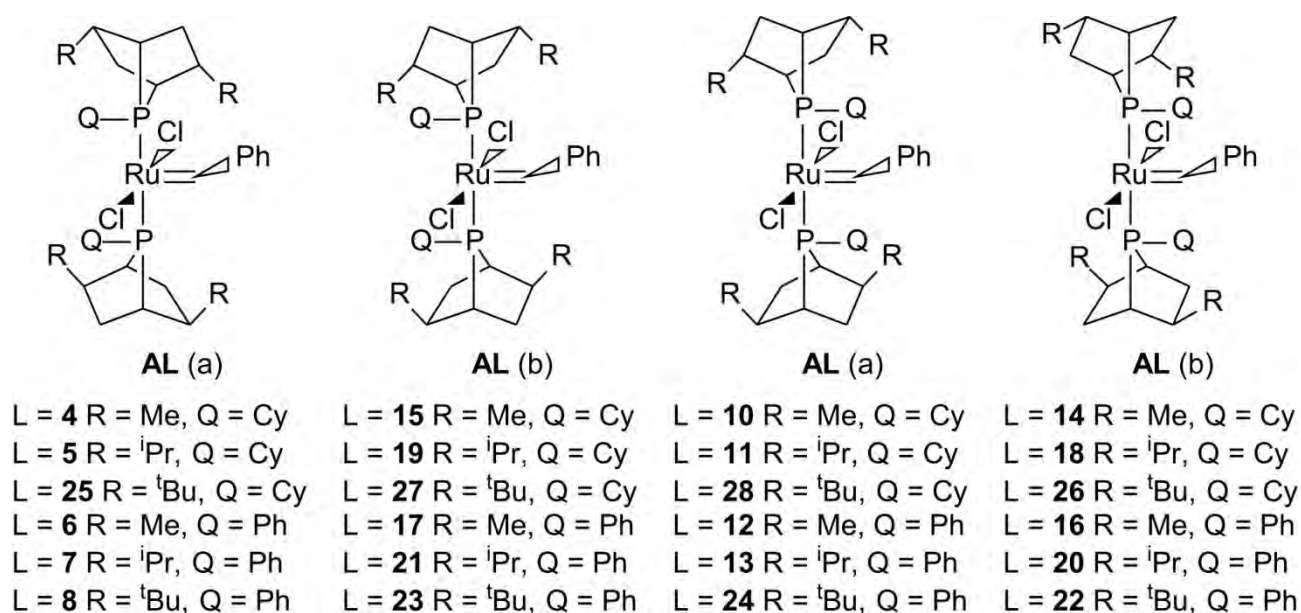


Figure 3.4 The *trans-trans* or *cis-cis* orientated “a” or “b” precatalysts.

According to Dwyer *et al.*,²⁹ the most stable structure should also have the highest dissociation energy during catalyst initiation. If the dissociation energy for the new rotational isomers (**A4** to **A8** and **A10** to **A28**) is compared (**Table 3.5**) with the rotational isomers **A3** and **A9**, it can be seen that the *trans-trans* isomers have the highest dissociation energy in most cases. What also becomes apparent is that the dissociation energy trends do not necessarily follow the same trends as those seen in **Table 3.4** (the correlation coefficient has a value of 0.48). This is an indication that generalisations should not be made without a sufficiently large dataset. At this point in time, an experimental investigation is still necessary to confirm which rotational conformer will be the most abundant.

In **Figure 3.5**, the average ruthenium phosphorus bond length is plotted against the dissociation energy for **A1** to **A28**. What becomes very clear from **Figure 3.5** is that there seems to be no clear correlation between the average Ru-P bond length and the dissociation energy. This is not surprising, since Sandford *et al.*³ and Love *et al.*²⁸ already investigated a series of phosphine ligands for both the first and second generation Grubbs catalysts experimentally and found that the correlation was so erratic that it could not be used for the prediction of catalytic behaviour.

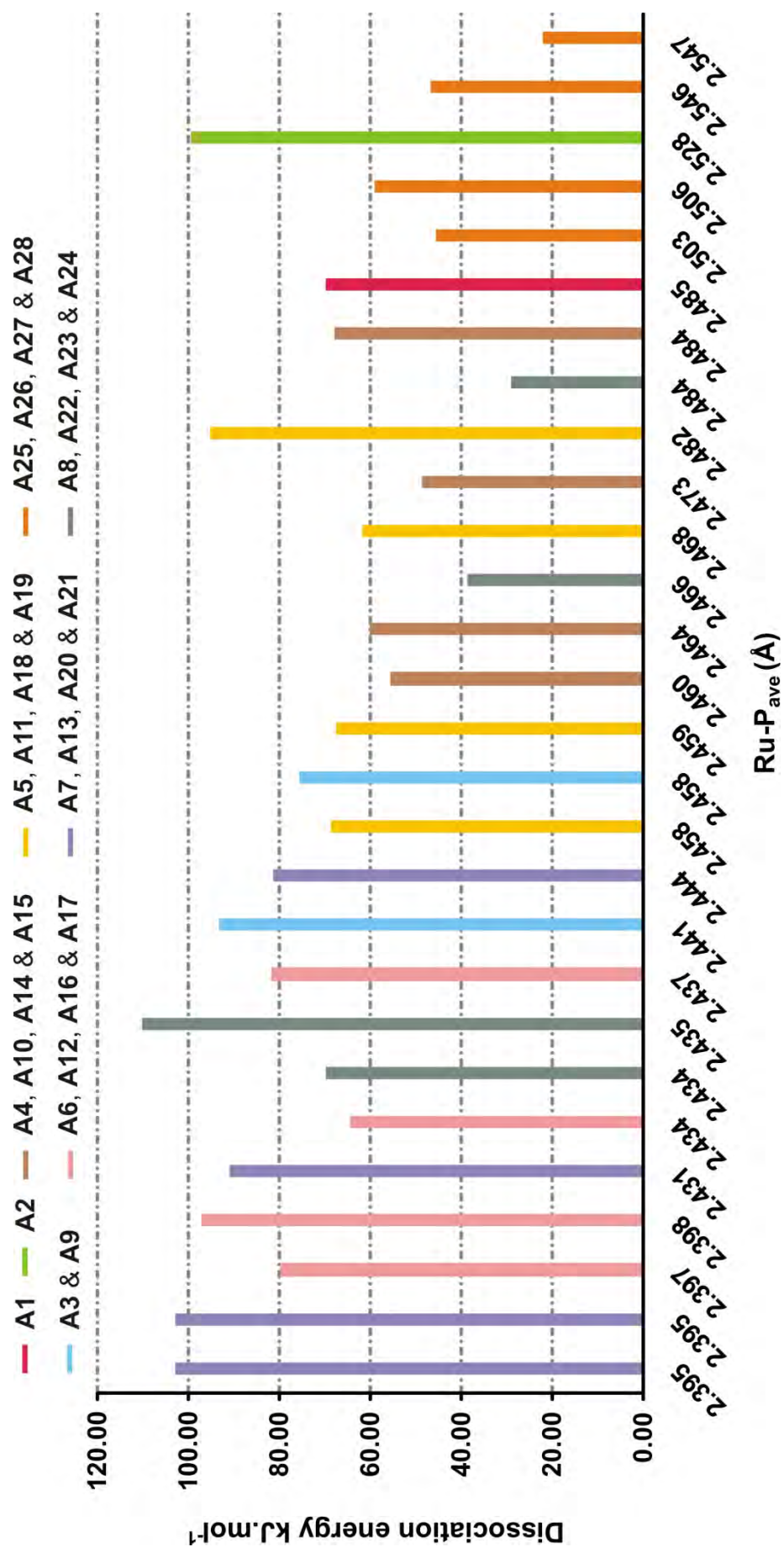


Figure 3.5 Dissociation energy (kJ.mol⁻¹) versus average Ru-P bond length (Å).

Table 3.5 The dissociation energy ($\text{kJ}\cdot\text{mol}^{-1}$) of the catalysts **A3** to **A28** for the *cis-cis* and the *trans-trans* isomers

Catalyst	Step	<i>Cis-cis</i>	Step	<i>Trans-trans</i>
Phobcat	A9-B9	75.58	A3-B3	93.13
CyMe (a)	A14-B14	48.69	A4-B4	60.25
CyMe (b)	A10-B10	67.84	A15-B15	55.36
PhMe (a)	A16-B16	64.30	A6-B6	96.90
PhMe (b)	A12-B12	81.47	A17-B17	79.83
CyIP (a)	A18-B18	61.72	A5-B5	68.50
CyIP (b)	A11-B11	95.17	A19-B19	67.40
PhiP (a)	A20-B20	81.17	A7-B7	102.87
PhiP (b)	A13-B13	91.01	A21-B21	102.75
CytB (a)	A26-B26	21.97	A25-B25	58.92
CytB (b)	A28-B28	37.23	A27-B27	46.60
PhtB (a)	A22-B22	29.06	A8-B8	109.92
PhtB (b)	A24-B24	38.64	A23-B23	69.51

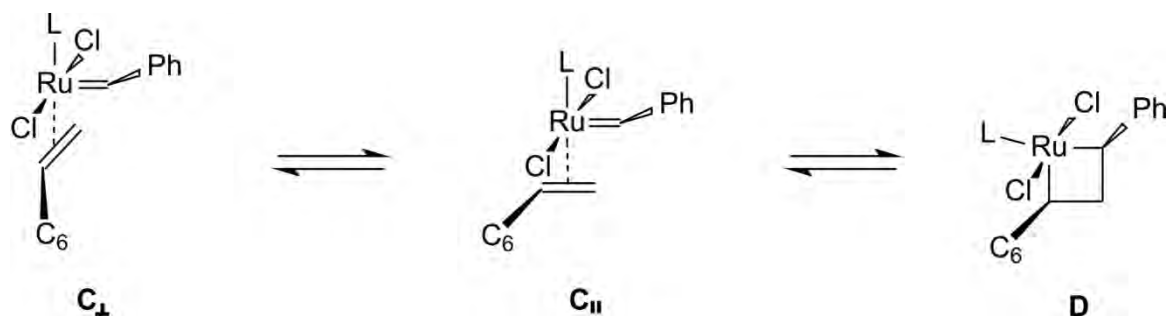
A popular method of sorting through a series of potential new ligands for the Grubbs-type systems is to calculate the dissociation energy values for the series of ligands and picking out those ligands whose energy values lie in or above an arbitrarily chosen range. This range is usually between the dissociation energies of **A1** and **A2**. The following question does arise: What effect will the dissociation energy have, if any, on the catalytic activity of the new precatalyst during the catalytic cycle? This question has to be asked since dissociation only takes place once during the activation phase, which also only takes place once during the metathesis reaction. In the current study, the catalytic activity can be defined as the ability of the catalytically active catalyst species to perform cross-metathesis on the chosen alkene substrate. In the following sections, this will be explored further.

3.7 Activation steps

After the initiation step, an alkene coordinates to the unsaturated intermediate **B** to form the corresponding π -complex, **C**. According to Chen *et al.*,⁴ the alkene can coordinate in two ways to the $\text{Ru}=\text{C}$ system. A study by Janse van Rensburg *et al.*¹³ indicated that the parallel coordination, $\text{C}_{\parallel}$, was energetically more favourable than the perpendicular coordination, $\text{C}_{\perp}$, (**Scheme 3.7**). In this study, only the case where the alkene coordinates parallel, $\text{C}_{\parallel}$, to the $\text{Ru}=\text{C}$ plane was investigated.

As was already indicated in the introduction to this chapter, using simplified systems leaves room for interpretation. Although more authors³⁶⁻³⁸ have recently started to use non-simplified ligands for their investigations, many still insist on using the methyldiene or other similar ligands as model precatalysts to investigate the catalysis of a variety of actual or model substrates. A very recent

article by Liu *et al.*³⁹ is just one of many such articles where an ethene and a methyldene precatalyst are used to predict the trends of a much more complex reaction.



Scheme 3.7 Alkene coordination in the dissociative pathway for the Grubbs-type catalysts.

In the subsequent discussion about **Figure 3.6**, a superscript ^B will be used to indicate when the carbene is a benzylidene moiety. A superscript ^M will be used to indicate when the carbene is a methyldene moiety. An additional superscript ^O will be used when the substrate is 1-octene and a superscript ^E will be used when the substrate is ethene. Therefore **C^{BO}** indicates that a 1-octene molecule is coordinated to the benzylidene form of the Grubbs 2 precatalyst, **A2^B**. In **Figure 3.6**, the point made by Jordaan *et al.*¹⁴ that model substrates do not give a good correlation with non-simplified systems is further illustrated. A comparison between the benzylidene (**A2^B**) and the methyldene (**A2^M**) activation steps with 1-octene to yield the catalytically active heptylidene (**F2^B**) and the redundant catalysis of ethene with the methyldene to yield the catalytically active methyldene (**F2^M**) for the **A2** precatalyst is shown. The necessary mass balance corrections were made so that the energies on the energy profile, where the methyldene has an open coordination site (**B2^M**), correlate with that of the complete system (**J2** in **Figure 3.10**). The rest of the energies were also adjusted accordingly. This was done to be able to correlate the energies of the methyldene catalysed steps with those of the benzylidene (the non-simplified catalyst system). Sandford *et al.*³ already proved, more than a decade ago, by trapping the methyldene with an excess of free phosphine ligand, that precatalysts that were poor initiators formed. They found that the **A2** methyldene precatalyst (**A2^M**) was almost incapable of re-entering the olefin metathesis catalytic cycle.³ They concluded that these complexes should be avoided.³ This observation is at the heart of the comparison illustrated in **Figure 3.6**; if experimental investigation already proved that the methyldene precatalysts are unsuitable for use in metathesis reactions, it has to be asked whether using these type of model precatalyst systems might be detrimental to gaining a deeper insight into the true nature of the various new ligands currently being developed.

What should immediately become clear from **Figure 3.6** is that the energy of the methyldene precatalyst (**A2^M**) is higher than the benzylidene precatalyst (**A2^B**) by 36.03 kJ.mol⁻¹. This simply means that the methyldene precatalyst is not as stable as the benzylidene precatalyst. Not

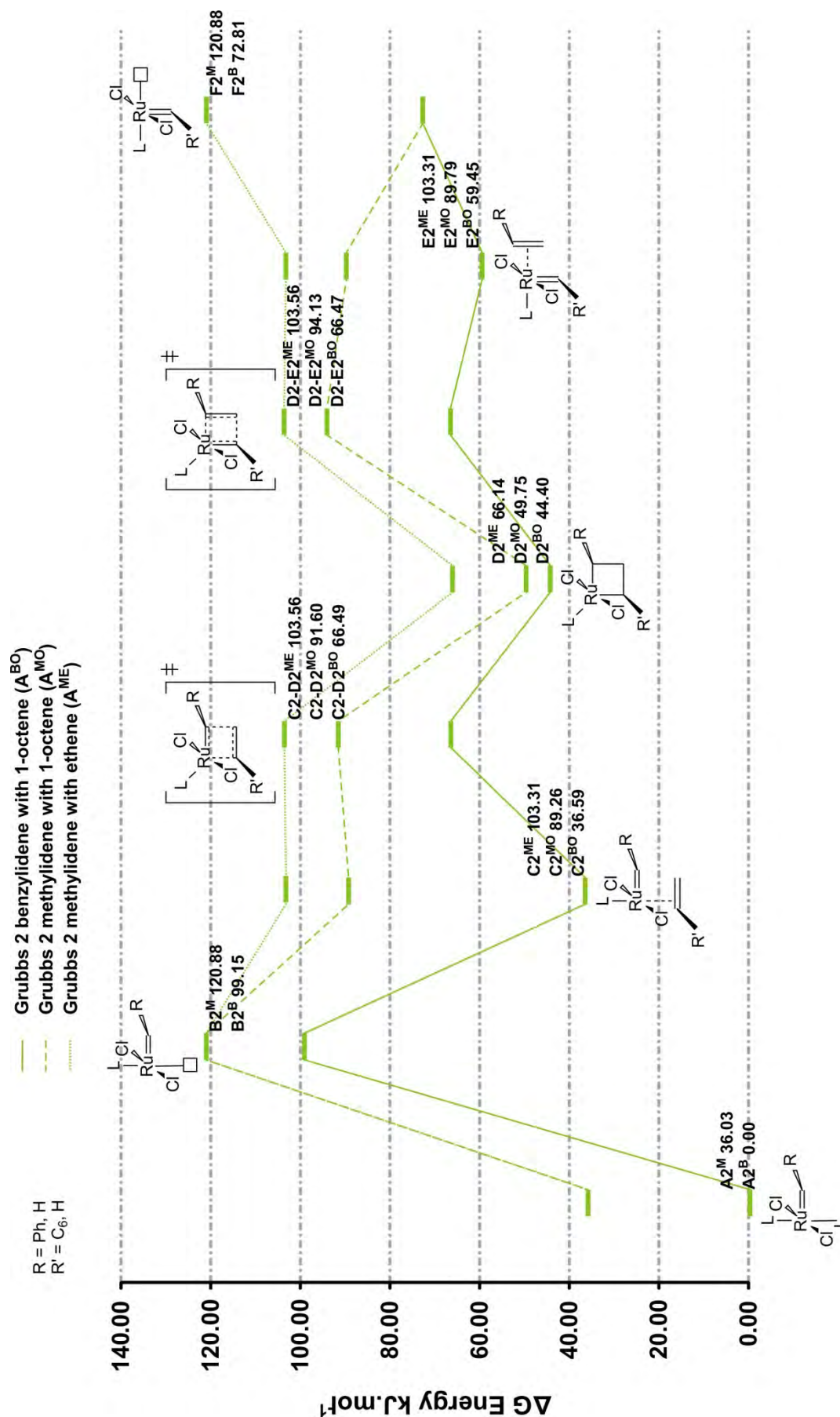


Figure 3.6 The dissociation (A to B) and activation steps (B to F) of the A2 benzylidene and methylidene to yield the catalytically active heptylidene or methylidene.

surprising when the experimental work of Sandford *et al.*³ is kept in mind. The comparison of the methyldiene and benzyldiene catalysis of **A1** and **A3** can be found in **Appendix A**. The energies of the methyldiene precatalysts of **A1** and **A3** are higher than the benzyldiene precatalysts by 30.40 kJ.mol⁻¹ and 40.10 kJ.mol⁻¹ respectively. This just provides further support for the argument that the validity of simplified systems has to be re-evaluated.

As **Figure 3.6** illustrates, the energy of the methyldiene complex with a 1-octene coordinated (**C2^{MO}**) is much higher than the benzyldiene complex (**C2^{BO}**). The higher energy required for 1-octene coordination (**C2^{MO}** requires an additional 52 kJ.mol⁻¹ more energy than **C2^{BO}** for 1-octene coordination) might explain the observation of Sandford *et al.*³ that the methyldiene precatalysts are poor initiators and consequently their inability to re-enter the catalytic cycle. This high coordination energy values for the methyldiene complex give lower energy barriers for the transition state during the formation of the metallacyclobutane ring (**C-D**). For the dissociation of the metallacyclobutane ring, the transition state energy barriers (**D-E**) for the methyldiene complex are larger than the benzyldiene complex. This is consistent with a slower reaction during the catalysis of 1-octene with the methyldiene complex.

What **Figure 3.6** illustrates is that the redundant metathesis of ethene with the methyldiene precatalyst (top line) shows similar trends to the metathesis of 1-octene with the methyldiene precatalyst (middle line). This should not be unexpected since the only difference is the length of the alkene chain. The energies of the ethene metathesis reaction give an energy profile with energy values higher by more than 10 kJ.mol⁻¹ in each of the steps investigated, when compared to the metathesis of 1-octene with the methyldiene complex. When the metathesis of 1-octene with the benzyldiene complex is compared with the ethene-methyldiene complex metathesis steps, the values are higher in all the steps by between 20 and 66 kJ.mol⁻¹. The simplified systems do not correlate well at all with the non-simplified benzyldiene complex activation steps. What should also be kept in mind is that activation only takes place once during the metathesis reaction. The current comparison shows that using simplified models to predict the catalytic activity of new precatalysts and not investigating the whole catalytic cycle can lead to incorrect assumptions being made.

High computing costs are usually one of the reasons given for using simplified ligands/substrates. However, with high performance computers (HPCs) becoming more available in recent years, it has to be asked whether this is still a valid argument. While there can be sympathised with theoretical chemists who do not have access to HPCs, at some point in time, theoretical studies being reported where simplified ligands/substrates are used have to be brought into question. The shortcomings of using simplified theoretical studies, as shown here, must be better understood for the simplified approach to change. Just like the experimental results of Sandford *et al.*³ showed more than a decade ago that using methyldiene complexes for metathesis should be avoided, the

current study shows that these complexes should also be avoided when investigating the metathesis reaction of Grubbs-type complexes theoretically. The higher energy values of the simplified methyldene complexes, when compared to the benzylidene complex, leave a lot of room for interpretation when it comes to gaining a deeper insight into the mechanism of alkene cross-metathesis. In the underlying sections, the rest of the catalytic cycle will be discussed in further detail. First, the activation steps of a selection of the new precatalysts with the new phosphine ligands currently being investigated will be compared with the precatalysts **A1**, **A2** and **A3** (**Figure 3.7** and **Figure 3.8**).

As was already mentioned in § 3.6, the possibility of rotational isomers for these new precatalysts exists. However, as was illustrated in **Scheme 3.7**, only two possibilities have to be considered. A comparison between the dissociation and activation steps of **A1**, **A2**, **A3** and a selection of the new *transoid-transoid* (*tt*) precatalysts is provided in **Figure 3.7**. **Figure 3.8** shows the comparison of **A1**, **A2** and **A9** with a selection of the new *cisoid-cisoid* (*cc*) precatalysts. To avoid overburdening the reader with a repetition of similar observations, the rest of the activation energy profiles for all the *tt*- and *cc*-precatalysts investigated in this study can be found in **Appendix A**.

The first observation that can be made from **Figure 3.7** is that high dissociation energy does not seem to translate into higher energies for the rest of the activation steps. Precatalyst **A8** has the highest dissociation energy and precatalyst **A25** has the lowest dissociation energy, but the rest of the activation steps have energies similar in value to that of **A4** and **A5**. In contrast, Grubbs 1 (**A1**) has a dissociation energy 30 to 40 kJ.mol⁻¹ lower than **A2**, **A3**, **A6** and **A7** and yet the rest of the steps have similar energies. Similarly, precatalyst **A25** has nearly the same dissociation energy as **A4** and yet the rest of the steps are between 10 and 20 kJ.mol⁻¹ lower in energy than that of **A4**. For all the precatalysts, the rate limiting step of the activation steps is phosphine dissociation. The last observation that can be made is that for all the precatalysts the shape of the energy profiles of the activation steps is fairly similar. Initially, this might seem confusing since it would be expected that **A2** with an NHC-ligand would show an activation energy trend that differs significantly from **A1** and the other precatalysts investigated. However, as **Figure 3.7** clearly shows, and the subsequent sections will show, this is not the case. What **Figure 3.8** shows is that while there is a difference in dissociation energy between the *tt*- and *cc*-precatalysts, once again the dissociation energy trends are fairly similar. All the same observations that were made for **Figure 3.7** can be made for **Figure 3.8**. This raises an interesting question about where the real difference between the various Grubbs-type precatalysts lies.

Grubbs *et al.*^{3,16,28} showed experimentally that the ratio of the rate of phosphine re-coordination (k_{-1}) and ethene coordination (k_2) to the 14-electron complex **B** can be correlated to the activity of the metathesis catalyst. They found that the k_{-1}/k_2 ratio for **A1** was four times bigger than the **A2**

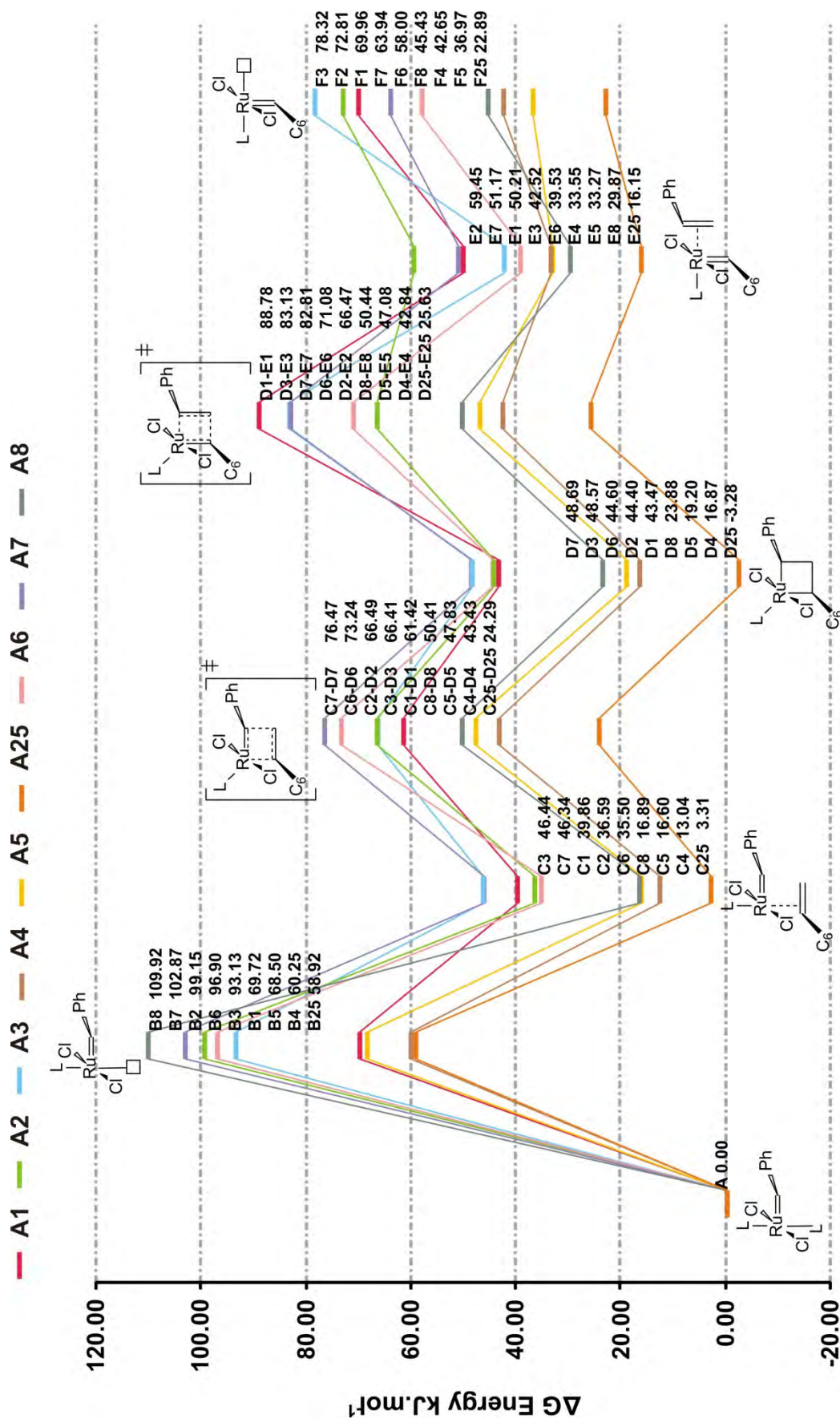


Figure 3.7 The dissociation and activation steps during the productive metathesis of 1-octene with **A1**, **A2**, **A3** and a selection of the new *tt*-precatalysts to yield the catalytically active heptylidene (**F**).

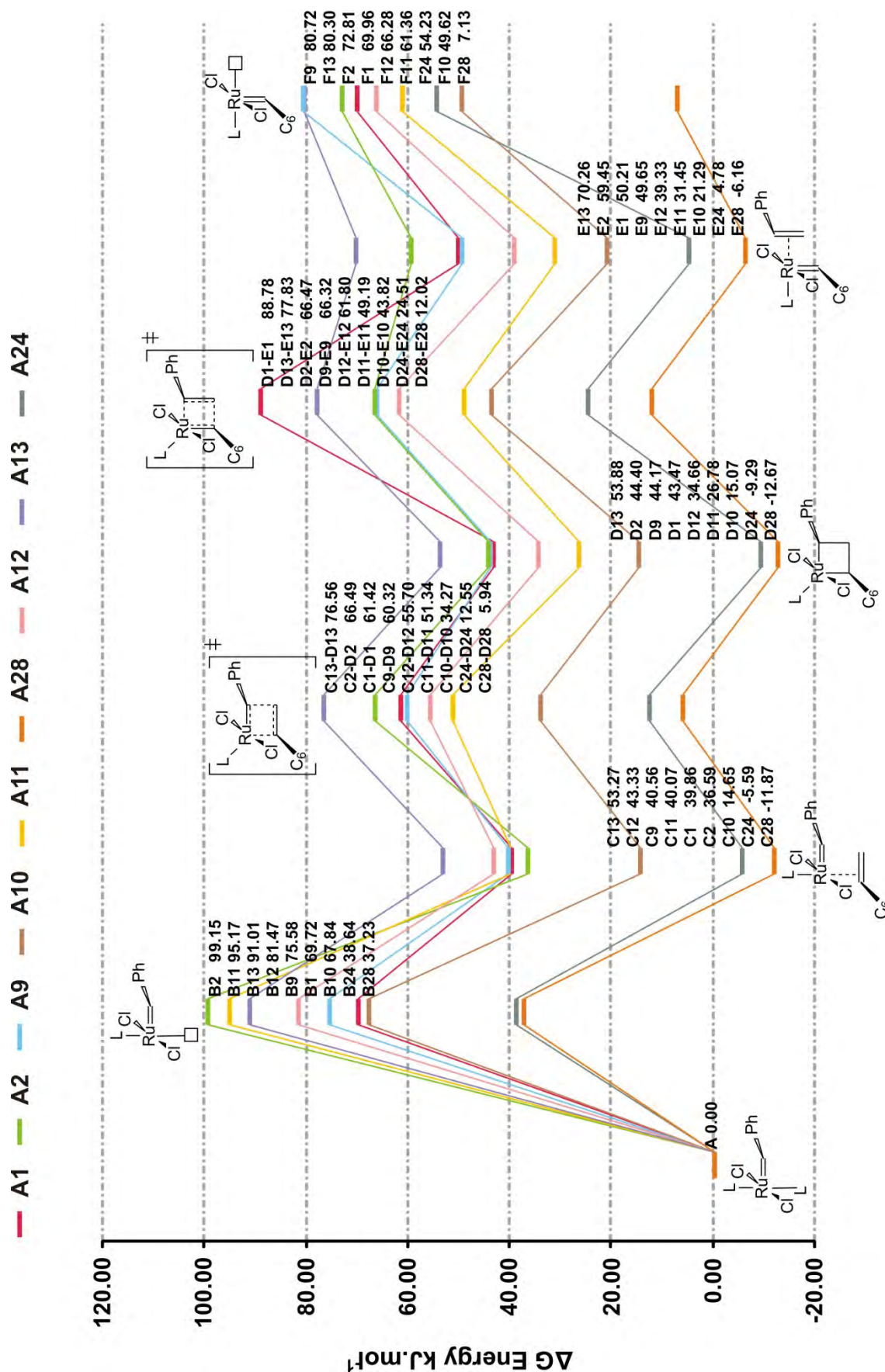


Figure 3.8 The dissociation and activation steps during the productive metathesis of 1-octene with **A1**, **A2**, **A9** and a selection of the new cc-precatalysts to yield the catalytically active heptylidene (**F**).

ratio. They concluded that the better alkene coordination selectivity of **A2** with regard to the higher experimental activity could be explained by this. The current molecular modelling results show that **A2** will have a higher affinity for 1-octene coordination than **A1**. What can be determined by taking the $\Delta G_{B-A}/\Delta G_{B-C}$ ratio from **Figure 3.6** is that **A2** will have a higher affinity for the 1-octene coordination than for the ethene coordination (**Table 3.6**). The **A2** methylidene has a poorer affinity for 1-octene coordination than **A1**.

Table 3.6 Comparison of the Gibbs energies of the π -coordinated intermediate of the precatalysts **A1**, **A2** and **A2^M** with ethene and 1-octene

Catalyst system	Energy ratio $\Delta G_{B-A}/\Delta G_{B-C}$	ΔG_{B-C} [B to C] kJ.mol ⁻¹
A1 + 1-octene	2.33	29.86
A2 + 1-octene	1.58	62.56
A2^M + 1-octene	2.67	31.2
A2^M + ethene	4.79	17.57

During cross-metathesis, activation takes place only once during the lifetime of the catalyst, where after the catalytic cycle can repeat many times until the catalyst is deactivated. Therefore, the activation steps will have an impact on the initial rate of the catalysis. The faster the catalyst can be activated, the faster the initial catalysis will be. However, investigating only the activation steps will not provide sufficient information to determine the total catalytic activity of a catalyst. In the next section, this will be investigated in more detail.

3.8 Catalytic cycle

The catalytic cycle was investigated by using the heptylidene, **F**. A 1-octene molecule coordinates to the catalytically active species **F** to yield **H** (**Scheme 3.5**). A cycloreversion then takes place where after 7-tetradecene dissociates to yield the catalytically active methylidene, **J**. The methylidene can then react with another 1-octene molecule and after cycloaddition and -reversion have taken place and ethene has dissociated, the catalytically active heptylidene is again available to re-enter the catalytic cycle. The cycle will continue to repeat until all the 1-octene has been consumed or the catalyst has been deactivated.

As was already mentioned (§ 3.7), the 1-octene can coordinate stereochemically in two ways, the hexyl groups *trans* or *cis*. The formation of selective *trans* or *cis* products has been the focus of several publications.^{40,41} Jordaan *et al.*^{14,15} determined that the *trans* coordination of 1-octene to **A1** and **A2** is more favoured than *cis* coordination. Forman *et al.*⁴² and Boeda *et al.*⁴³ observed the same trend when they investigated the reaction of 1-octene with the **A3** precatalyst. Recently, the new *z*-selective precatalysts **A102** and **A103** (**Figure 3.9**) were reported.^{44,45} They yielded *cis*

products by preference during several different cross-metathesis reactions.^{44,45} Keitz *et al.*⁴⁵ found that precatalyst **A102** could be made more stable by changing the carboxylate ligand to a nitrate ligand to yield **A103**. The more stable **A103** will be used in the discussion below. In this study, both the *cis* and *trans* coordinations of 1-octene to yield 7-tetradecene were investigated for all the new precatalyst systems to determine whether they will show a much higher preference for one of the coordination orientations.

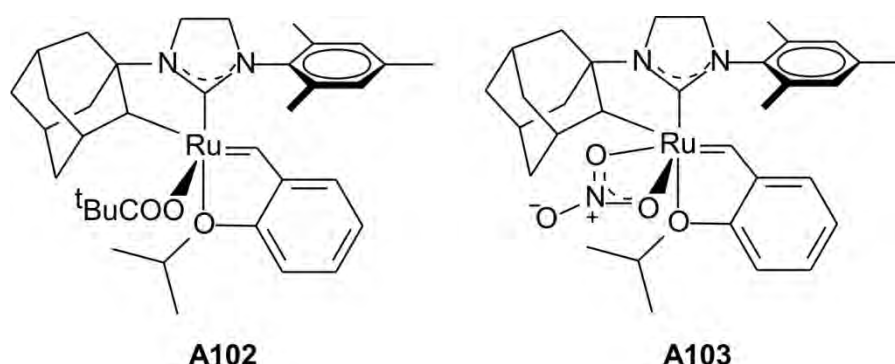


Figure 3.9 The new precatalysts **A102** and **A103** that yield *cis* cross-metathesis products by preference.^{44,45}

The full catalytic cycle (steps **G** to **N** in **Scheme 3.5**) of the active **A1**, **A2**, **A3** catalysts and a selection of the new *tt*-catalysts are illustrated in **Figure 3.10** (only the *trans* coordination of 1-octene is illustrated). In **Figure 3.11**, the full catalytic cycle of the active **A1**, **A2** and **A9** catalysts and a selection of the new *cc*-catalysts are shown (again only the *trans* coordination of 1-octene is illustrated). In **Figure 3.12**, the *cis* and *trans* coordination of 1-octene to the active **A1**, **A2**, **A3** and **A103** catalysts (steps **G** to **J** in **Scheme 3.5**) is shown. **Figures 3.13** and **3.14** contain the *cis* and *trans* coordination of 1-octene to the selection of active new *tt*- and *cc*-catalysts studied in the previous section; **Figure 3.14** also contains the **A9** comparison.

Before the new catalyst systems will be studied in detail, it is necessary to first study the established catalyst systems, **A1**, **A2**, **A3** and **A103**, in more detail. Currently, no evidence could be found in literature of an in-depth Gibbs-free energy investigation of these catalysts using 1-octene as a substrate. In **Figure 3.12**, the *cis* and *trans* coordination of 1-octene to these four catalysts to yield 7-tetradecene is illustrated. As mentioned above, it has already been shown experimentally that the *cis* coordination of 1-octene is more unfavourable than the *trans* coordination for **A1**, **A2**, and **A3**.^{14,15,42,43} As **Figure 3.12** shows, for these three cases the energy required for *cis* coordination of 1-octene is higher than that required for *trans* coordination. While the *cis* coordination for **A103** is slightly more favoured than *trans* coordination. The second point worth noting is that, with the exception of the **A3** catalyst, the energies for all the remaining steps to form 7-tetradecene are fairly similar. Experimentally, it was determined (see **Chapter 4**) that the

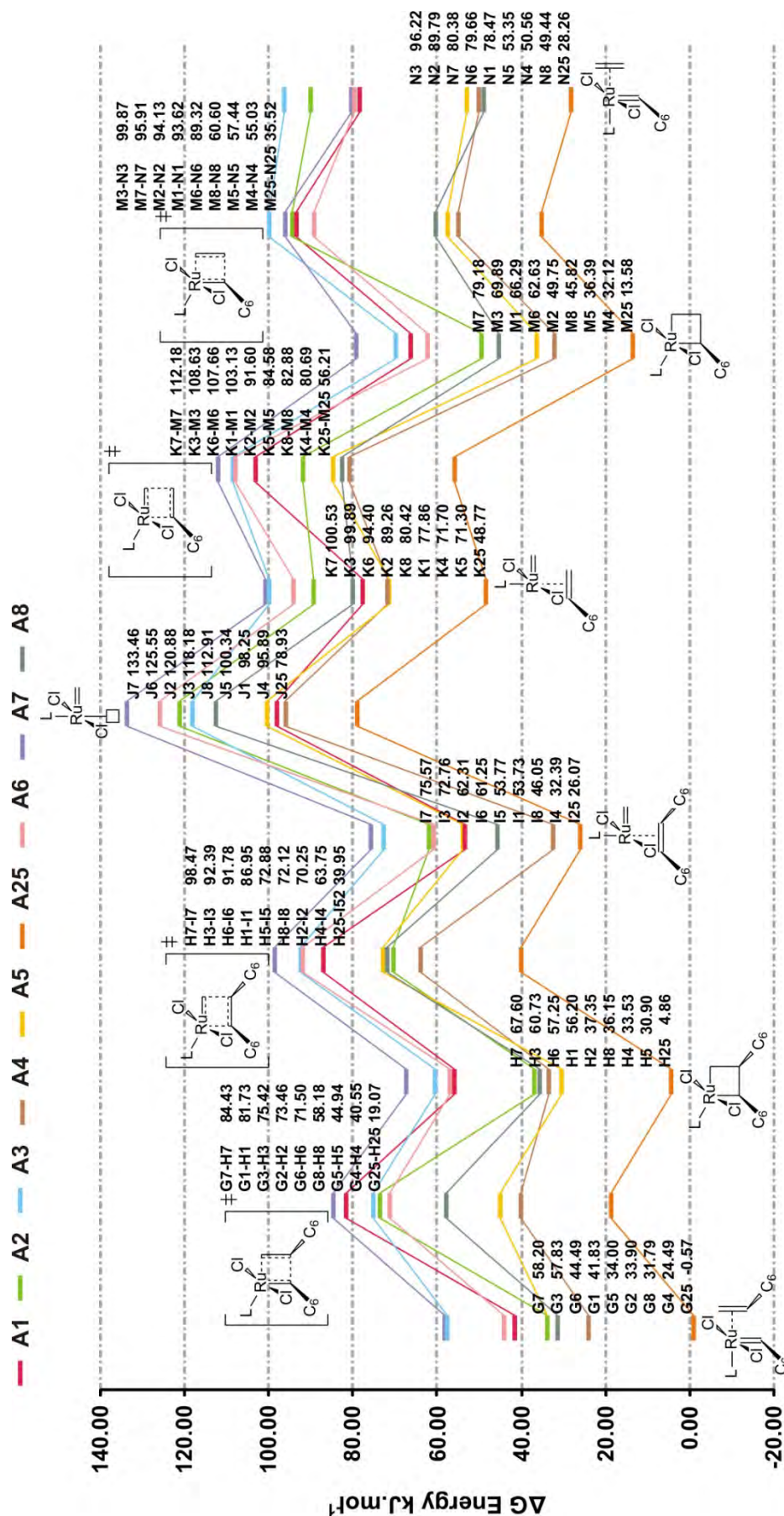
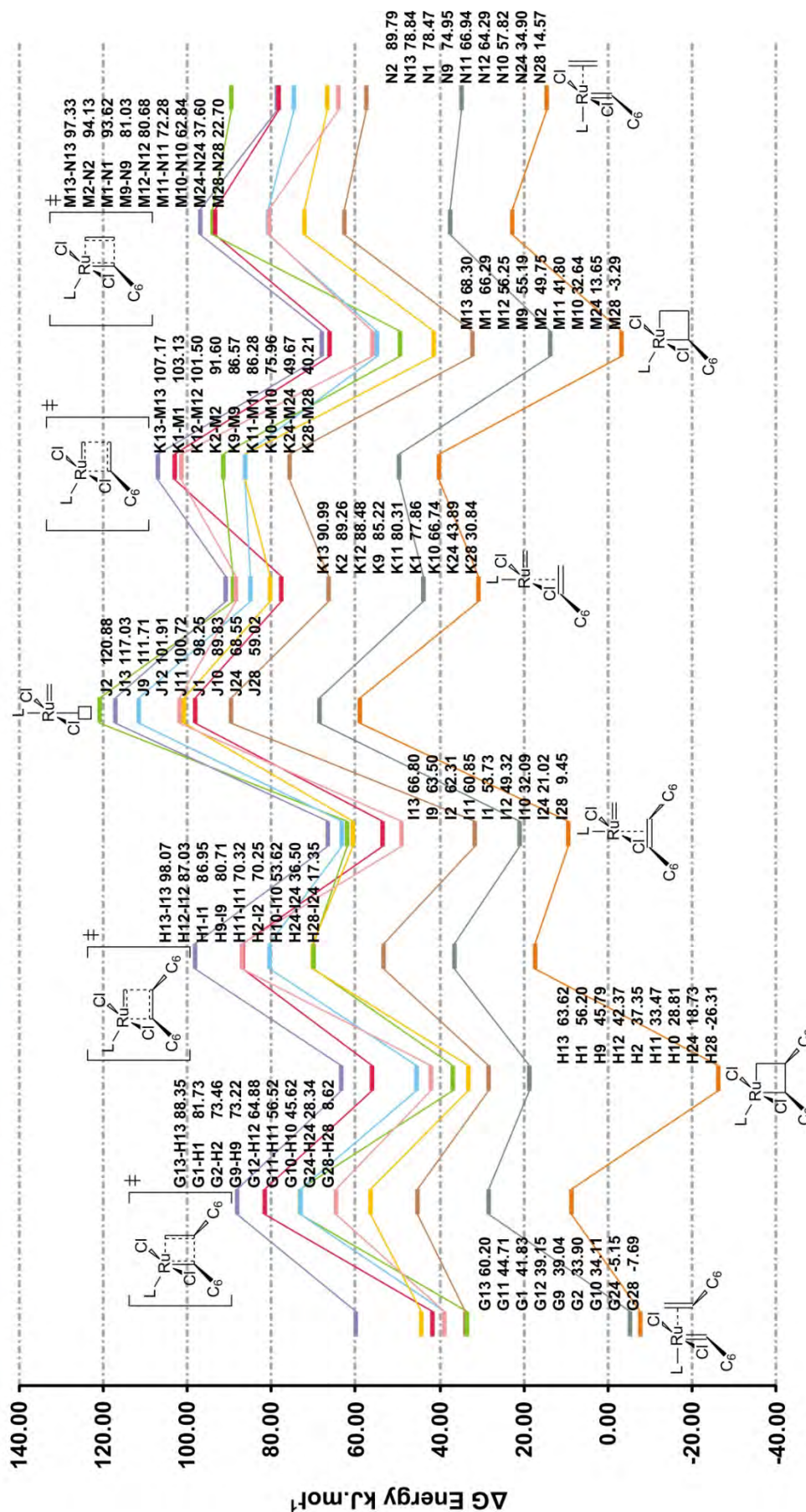


Figure 3.10 A comparison between the steps of the catalytic cycle of **A1**, **A2**, **A3** and a selection of the new *tt*-precatalysts.



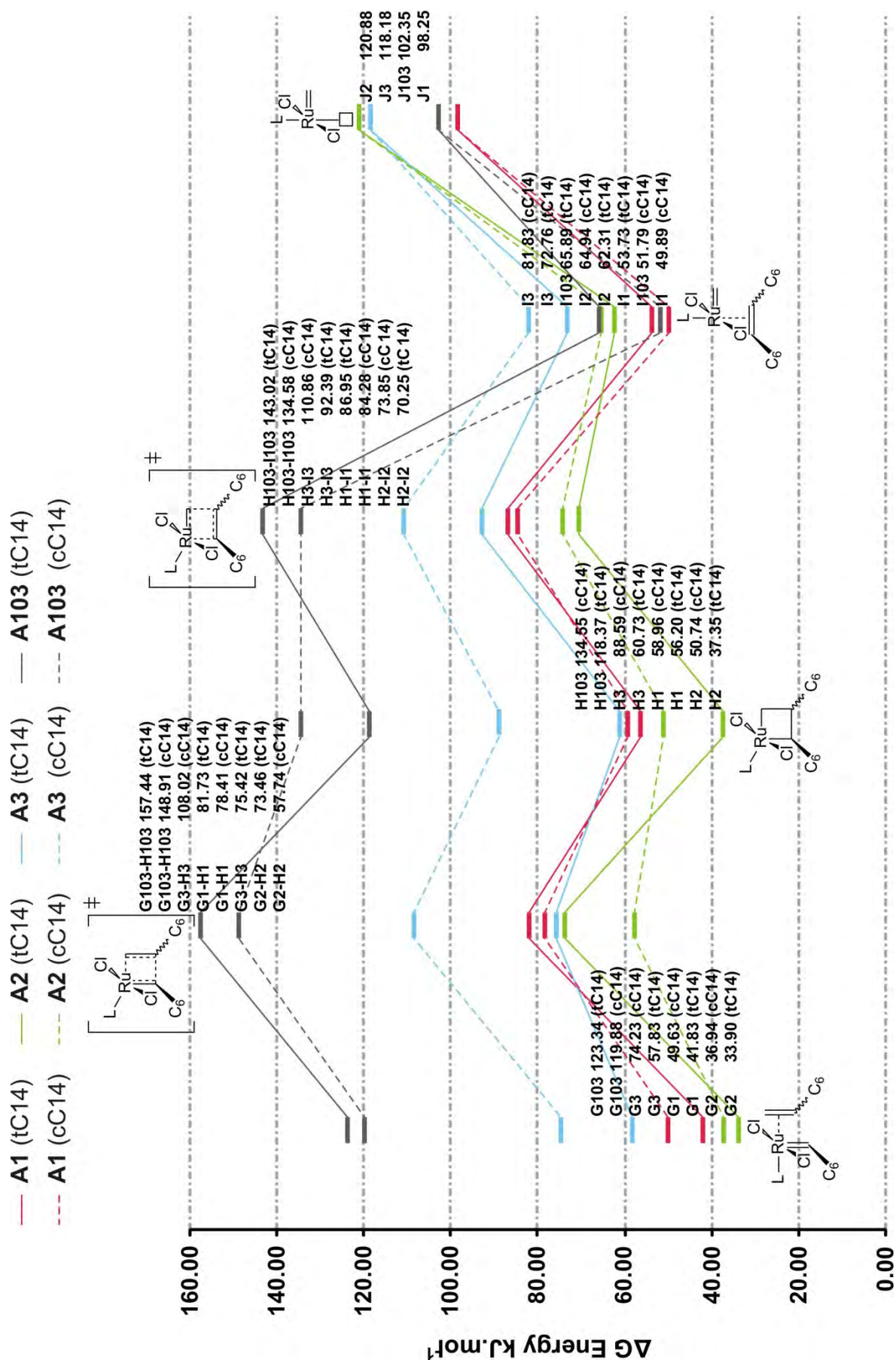


Figure 3.12 A comparison between the *cis*- and *trans*-7-tetradecene formation catalytic cycle steps of **A1**, **A2**, **A3** and **A103**.

ratio of *cis*- to *trans*-7-tetradecene formation for **A1** at room temperature is 40:60 and for **A2** the ratio is 20:80; while for **A3** the ratio is 30:70. Keitz *et al.*⁴⁵ reported a 5:95 *trans*:*cis* ratio for the cross-metathesis of 1-octene with **A103**. Unfortunately, **A103** was not yet commercially available at the time of investigation to test it under the same reaction conditions as was done for the rest. The theoretical results support the observed experimental results, *cis*- and *trans*-7-tetradecene will form and the differences in coordination energy are consistent with a product ratio that is not equivalent. The high experimental yield of either *cis*- and *trans*-7-tetradecene poses an interesting problem. It would be expected that the difference between the *cis*- and *trans*-7-tetradecene formation energies would in all cases be sufficiently different, like that of **A3**. In other words, that the more favoured product will have lower energy values in most or all the steps. If the energy barriers are so similar, the driving force behind the differences in the product distribution has to be investigated. A suggestion might be that one product would be the kinetic and one the thermodynamic product. However, as will be shown, this does not seem to be the case.

When the original experimental data of Jordaan¹⁵ and Looock⁴⁶ were investigated in more detail, some surprising observations were made. Jordaan¹⁵ investigated the cross-metathesis of 1-octene with **A1** and **A2**. Looock⁴⁶ investigated the cross-metathesis of 1-hexene, 1-heptene, 1-nonene and 1-decene with **A1** and **A2**. Since the *cis* and *trans* products of 1-hexene and 1-heptene do not separate sufficiently on GC for analysis, they will be disregarded in the current discussion. Looock⁴⁶ found the optimum cross-metathesis temperature for the various 1-alkenes in her study while Jordaan¹⁵ did the same for 1-octene. If their experimental data is combined with the experimental data in this study, a temperature range of 25 to 100 °C is covered. The first surprising observation from Jordaan's¹⁵ work was that, regardless of the temperature used, the ratio of *cis*- and *trans*-7-tetradecene formed from 1-octene with **A1** and **A2** stayed constant at 40:60 and 20:80 respectively. The second surprising observation from Looock's⁴⁶ data was that these ratios remained unchanged regardless of the 1-alkene chain length. It can be argued that beyond a certain chain length the steric influence becomes irrelevant or that the difference in chain length is too small and therefore the *cis*:*trans* ratio will be fairly similar. It would therefore be worthwhile to devise a method to separate the shorter chain products to determine whether the ratios are the same for them. The temperature independence of the *cis* to *trans* ratio poses the more interesting problem. If temperature influenced the ratio, the argument could be made that the coordination orientation might change before it is trapped in the lower energy orientation at a certain later point in the mechanism. What can be observed when the temperature is increased is that the amount of 1-alkene that reacted increases.^{15,46} Jordaan¹⁵ and Looock⁴⁶ both steadily increased the reaction temperature to find the temperature where the largest amount of the 1-alkene will react and the least amount of isomerisation and secondary metathesis will take place. Isomerisation of for instance, 1-octene takes place when it is converted to 2-, 3- and 4-octene. When metathesis of these isomerised products takes place it is considered as secondary metathesis. Jordaan¹⁵ found

that **A1** formed much more isomerisation products at elevated temperatures, but the amount of secondary metathesis was unchanged. When **A2** was investigated, almost no isomerisation products were observed at elevated temperatures, but the amount of secondary metathesis products increased dramatically.¹⁵ This is indicative of the higher stability of **A2** at elevated temperatures when compared with **A1**. Since the formation of isomerisation and secondary metathesis products at elevated temperatures does not affect the *cis* to *trans* ratios, the driving force behind this remains unclear and warrants further study. The whole discussion of *cis* to *trans* ratios supports the observation made in the section above that a small difference in the energy barriers of the proposed reaction mechanism cannot on its own account for the large differences in activity of the various catalysts.

It can be seen from **Figure 3.10** that the methyldiene part of the catalytic cycle (steps **J** to **N**) for **A1**, **A2** and **A3** shows some difference in the energy values, but the overall trend is once again fairly similar.

The observed NMR results of the reaction of **A1** with 1-octene by Jordaan¹⁵ are also supported by the current molecular modelling investigation. She found that the initial high benzylidene concentration will go down rapidly as the reaction progresses.¹⁵ The formation of the heptylidene was almost instantaneous while the methyldiene formed at a much slower rate, where after both concentrations decreased.¹⁵ As was already stated, the activation steps take place only once during the lifetime of the catalyst and therefore the benzylidene concentration will go down rapidly as more of the precatalyst is activated and enters the catalytic cycle.¹⁵ From **Figures 3.7** and **3.10** that formation of the heptylidene is energetically more favoured than the formation of the methyldiene. This explains the initial higher concentration of the heptylidene. As the reaction progresses, an equilibrium between the concentration of the heptylidene and the methyldiene will be reached. This explains the faster initial heptylidene formation, followed by the slower methyldiene formation as the heptylidene concentration decreases. As the catalyst is deactivated and the active carbene catalysts are converted into an inactive form, the concentrations of both the heptylidene and the methyldiene will decrease as well.¹⁵

From **Figures 3.13** and **3.14**, where the *cis* and *trans* coordination of 1-octene to the selection of new catalysts (**A4** to **A13**, **A24**, **A25** and **A28**) is illustrated, we can make some interesting observations. All the energy steps of the various catalysts are fairly similar. The only exceptions are **A9** and **A28** where there is more variance between the various steps. The second observation that can be made is that for all the 1-octene coordination steps, except steps **G7**, **G8** and **G13**, the coordination energy of 1-octene in the *cis* orientation (out of the plane of the paper) is higher than the coordination energy in the *trans* orientation (into the plane of the paper). This only means that the formation of *cis*-7-tetradecene, when these precatalysts (**A7**, **A8** and **A13**) are used, might be

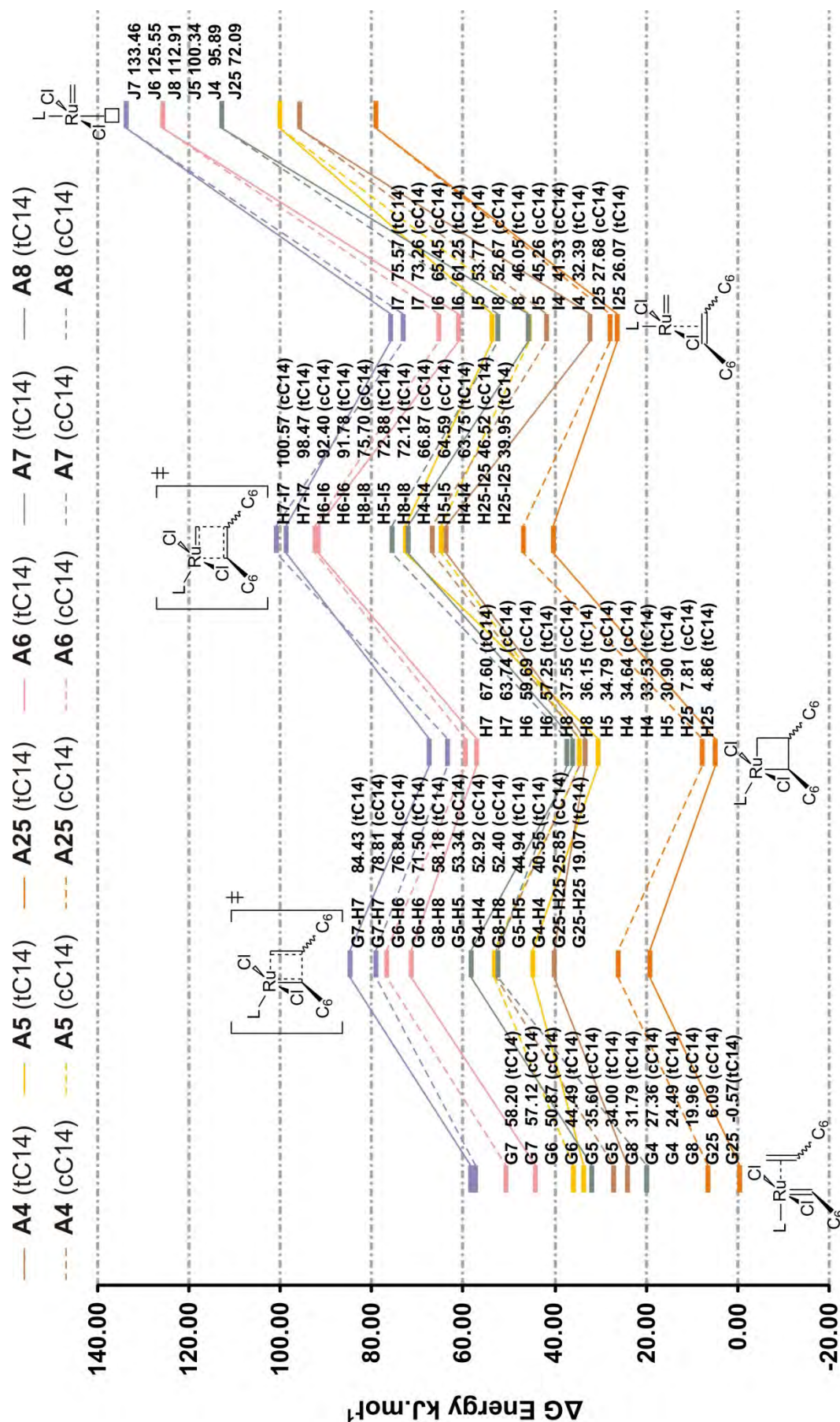


Figure 3.13 A comparison between the *cis*- and *trans*-7-tetradecene formation catalytic cycle steps of a selection of the new *tt*-precatalysts.

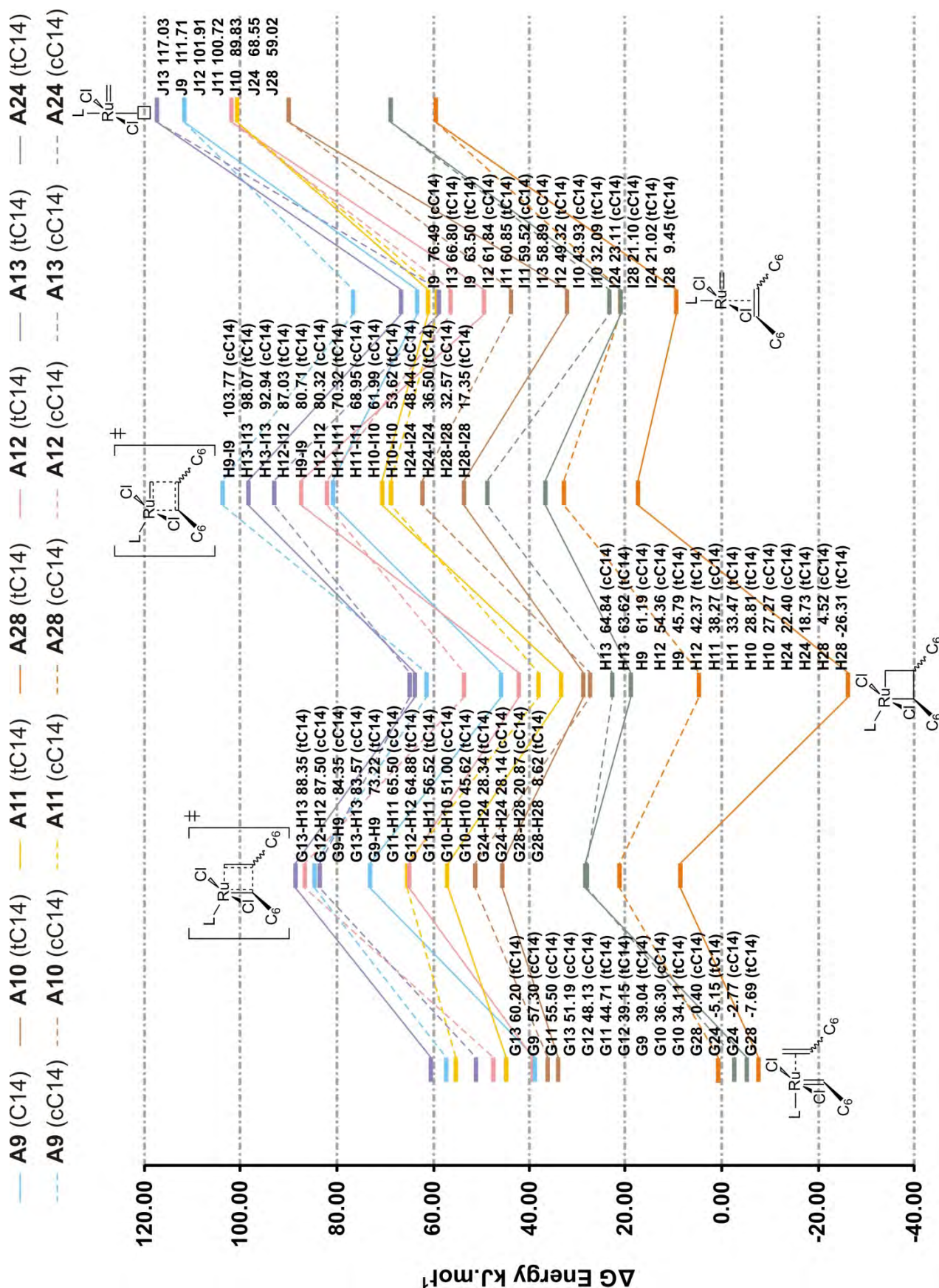


Figure 3.14 A comparison between the *cis*- and *trans*-7-tetradecene formation catalytic cycle steps of a selection of the new cc-precatalysts and A9.

slightly higher than the *trans* product. For none of the precatalysts investigated, is it expected that the *cis* product will be formed exclusively, since the difference in the energy barriers is too small to indicate that one coordination is highly favoured over the other. If the rest of the catalytic cycle is investigated (**Figures 3.10** and **3.11**), it can be seen that, just like the coordination energy of 1-octene to the heptylidene, **F**, to yield **G** is fairly similar for the various catalyst systems, the coordination energy of 1-octene to the methyldiene, **J**, to yield **K** is also fairly similar. The only real difference is the catalyst systems with cyclohexyl-bearing ligands (**A4**, **A5**, **A10**, **A11**, **A25** and **A28**). Whether this slightly lower energy for the methyldiene catalysis of 1-octene will lead to faster overall catalysis has to be determined experimentally.

What becomes apparent from the discussion above is that a comparison of the energies of the various catalyst systems does not on its own give a satisfactory answer to the question: why is metathesis with one catalyst system faster than another one? The second question that remains unanswered is: why does one catalyst have a longer lifetime than another? It is also clear from **Figures 3.10** to **3.14** that the trends of the energy profiles are once again fairly similar. The rate limiting step for all the catalytic cycle steps is the formation of the methyldiene, **J**. This is consistent with the discussed experimental results of Sandford *et al.*³ (§ 3.7) that the methyldienes are poor initiators. If we look at the experimental results reported by Jordaan *et al.*^{14,15} for the metathesis of 1-octene at 35 °C with **A1** and **A2**, we get some explanation for these similar theoretical energy values (**Table 3.7**). In **Table 3.7**, the percentage of primary metathesis products (PMP: homometathesis products of 1-octene: 7-tetradecene, ethene), of secondary metathesis products (SMP: metathesis of the isomerisation products of 1-octene) and of isomerisation products (IP: double bond isomerisation of terminal to internal alkenes) formed are indicated.¹⁵ Jordaan¹⁵ determined the initiation rate constants ($k_{\text{init}}/\text{mol.s}^{-1}$) as a function of the mol 7-tetradecene formed over time.

Table 3.7 Catalytic activity and selectivity of **A1** and **A2** towards the metathesis of 1-octene at 35 °C (1-octene/Ru = 9000, no solvent) after 420 min

Precatalyst	T/°C	PMP/%	SMP/%	IP/%	%S ^a	k_{init} (mol.s ⁻¹)
A1 ^{14,15}	35	40.8	0.3	0.4	98.31	1.24×10^{-5}
A2 ^{14,15}	35	60.8	1.3	0.0	97.91	2.40×10^{-5}

^a Selectivity towards PMP.

The initiation rate, k_{init} and the percentage of primary metathesis products (PMP) formed are slightly higher for **A2** than for **A1**. The similar initiation rates can be explained by the observed similarities in the energy barriers of the proposed reaction mechanism (**Figures 3.7**, **3.10** and **3.12**). What must be kept in mind is that the activation of the catalysts only takes place once, where after the catalytic cycle repeats many times over. If the activation steps of **A1** have a rate of

1 and the rate of the activation steps of **A2** is 2 and the catalytic cycle for both has a rate of 10 then the observed rate of **A1** will be slower. As the number of cycles increases, the first step becomes less and less important. It therefore stands to reason that the lifetime of these catalysts, that we know differs significantly, has to be a major difference between these catalysts. Although this has been established experimentally, these theoretical results further underscore the statement above that comparing the energy values alone cannot provide satisfactory answers to the catalytic activity of the various catalyst systems.

3.9 Investigation of low activity Grubbs-type precatalysts

In the Handbook of Metathesis by Robert Grubbs²⁷, his co-worker Nguyen wrote a wonderful piece on the history of the development of the now well-known Grubbs first generation catalyst, **A1**. In this history, he describes how working as a post-doctoral fellow he initially synthesised **A104**,⁴⁷ which showed very poor ring-opening polymerisation metathesis activity with norbornene, before almost a year later out of sheer frustration he tried the most basic phosphine in the storeroom, PCy₃, which eventually led to the synthesis of **A1**, and the rest as they say is history.²⁷

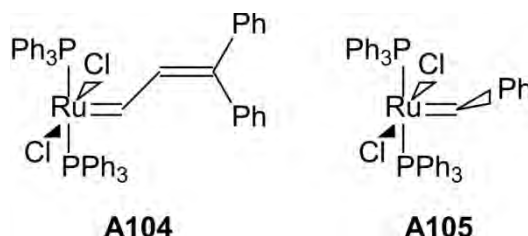


Figure 3.15 The precatalysts **A104** and **A105**.

In an effort to further investigate the observed results in the previous sections, it was decided to investigate the precatalyst **A105**.⁴⁸ The identical benzylidene moiety was the reason why all the calculations were performed using the precatalyst **A105** and not **A104**. Schwab *et al.*⁴⁸ report that **A105** is relatively unstable when compared to **A1**. It was felt that the energy profile should provide some answers as to why **A105** is a poor catalyst. The hope was that a marked difference in the energy barriers would be seen, which would provide a cut-off energy guide, i.e. provide a guide where below or above metathesis cannot take place, or at least help to better identify those step or steps in the energy profile that are responsible for the differences in the observed experimental activity. The activation and catalytic cycle steps of **A105** are illustrated in **Figures 3.16, 3.17** and **3.18**. A comparison with the other known catalysts (**A1** to **A3**) from literature was done to better illustrate the difference between **A105** and these catalysts. Surprisingly, the expected difference between the precatalysts was not observed. The dissociation energy difference between **A105** and **A1** is only 1.93 kJ.mol⁻¹, which is very small when compared to the dissociation energy difference

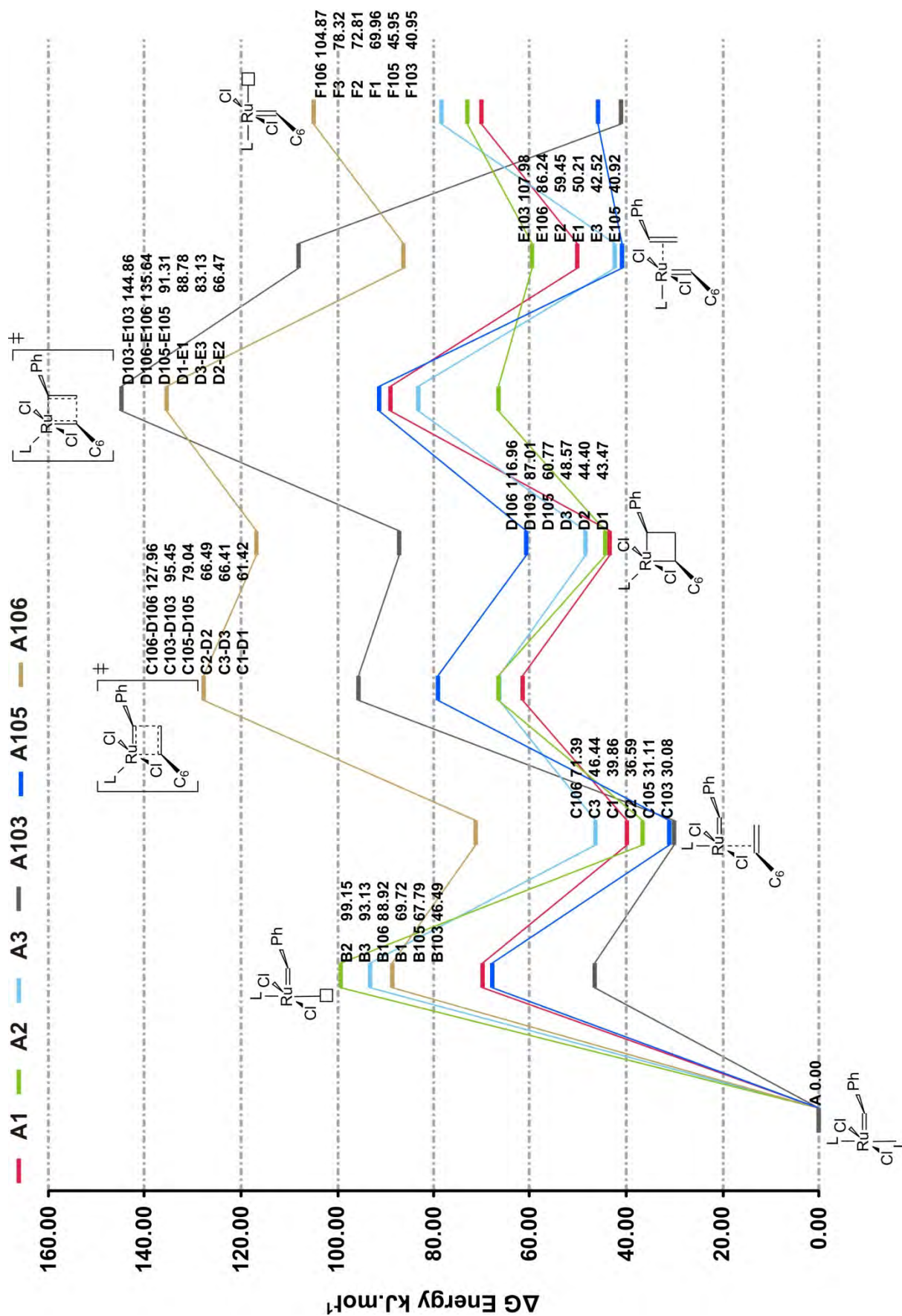


Figure 3.16 The dissociation and activation steps during the productive metathesis of 1-octene with A1, A2, A3, A103, A105 and A106.

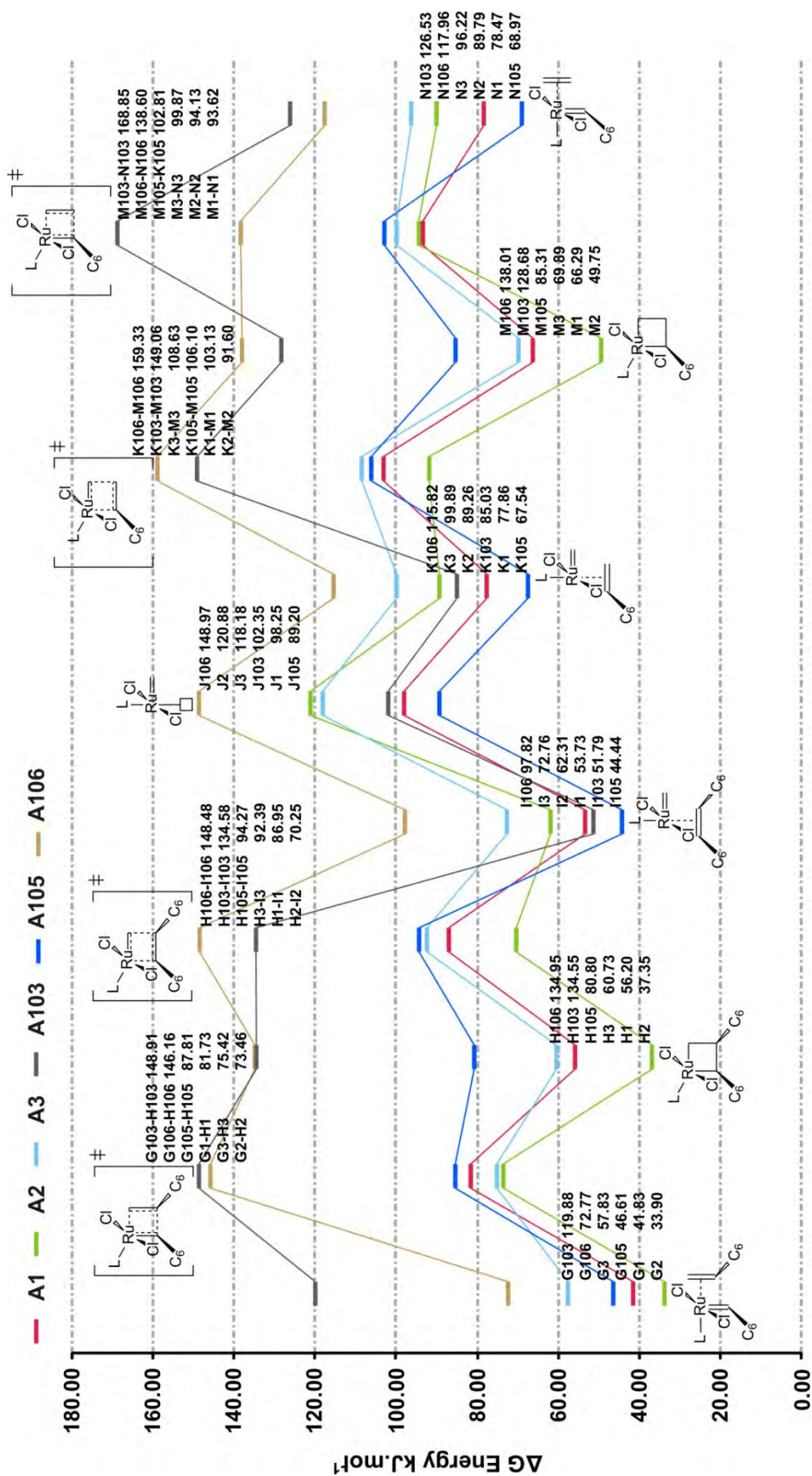


Figure 3.17 A comparison between the steps of the catalytic cycle of A1, A2, A3, A103, A105 and A106.

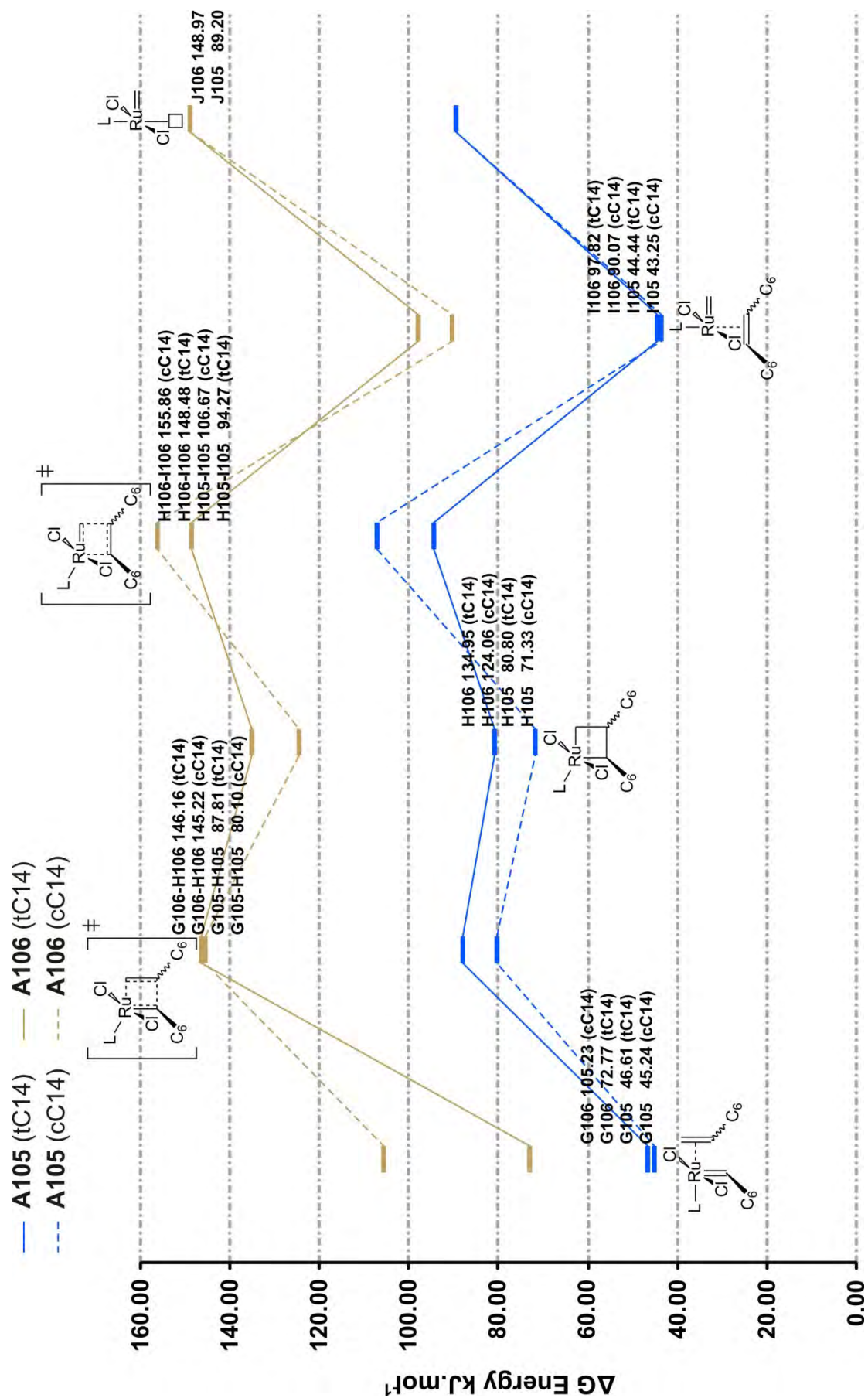


Figure 3.18 A comparison between the *cis*- and *trans*-7-tetradecene formation catalytic cycle steps of a selection of **A105** and **A106**.

of 29.43 kJ.mol⁻¹ between **A1** and **A2**. This observation is consistent with the question asked in §3.6 whether the dissociation step is the most important step during the complete catalytic cycle. What also become apparent from **Figures 3.16** and **3.17** is that the energies of the rest of the steps of **A105** are within the same range of energies as those of **A1** to **A3**. This is again consistent with the observations thus far that the steps of the energy profile of the accepted reaction mechanism do not necessary provide as much information about the activity of the catalyst as it is supposed to provide. The only real observable difference between **A105** and **A1** to **A3** is that the metallacyclobutane steps (**D**, **H** and **M**) show slightly elevated energies when compared to the rest of the steps. This slight elevation is not so high to suggest that the metallacyclobutane cannot form, but it certainly is an indication that its formation will be unfavourable. In **Figure 3.18**, similar coordination energies for 1-octene in both the *cis* and *trans* orientation to **A105** (step **G**) can be seen. As was seen for **A1** and **A2**, where the coordination energies of 1-octene in both the *cis*- and *trans*-orientation are fairly similar, **A105** also shows energy steps that are fairly similar. Since **A105** showed low metathesis activity experimentally,⁴⁸ it should not be surprising that its energy values are so similar to that of **A1** to **A3** and therefore lie in an area on the potential energy surface where metathesis activity is known to take place. This once again raises the question: what determines the catalytic activity of the catalyst?

In an effort to better address this problem, it was decided to investigate an additional ligand. The criterion for choosing this ligand was that it had to be a much poorer ligand than those currently being used so that none to very little catalytic activity should be possible. It is known that the NHC ligand of **A2** is a better electron donor than the PCy₃ ligand of **A1**, which is a better donor than the PPh₃ ligand of **A105**.²⁷ To identify a potentially poor ligand, the donating ability of all the ligands investigated in this study was determined. This was done so that a ligand that is markedly different from those currently under investigation could be chosen for further study.

In **Chapter 2**, the molecular electrostatic potential (MESP),⁴⁹ expressed as $V_{\min}$, was briefly described as a potential theoretical approach to calculate the nucleophilicity of the phosphorus centre and therefore determine the donating ability of uncommon or unknown ligands.⁵⁰ This was done by solving the following equation:

$$V(\mathbf{r}) = \sum_A^N \frac{Z_A}{|\mathbf{r} - \mathbf{R}_A|} - \int \frac{\rho(\mathbf{r}')d^3\mathbf{r}'}{|\mathbf{r} - \mathbf{r}'|}$$

where Z_A is the charge on nucleus A, located at a distance R_A , ρ is the electron density and r is the atomic radii. According to Suresh and Koga,⁴⁹ it can also be interpreted as a quantity directly related to the interactive behaviour of a molecule with a unit test positive charge. In the equation, the sum is a nuclear term, while the integral is an electronic term, therefore the higher negative the MESP value is, the better electron donor the ligand will be. The global minimum or the most negative valued point, the $V_{\min}$, is found where the differential of the equation is equal to zero. The

$V_{\min}$ values were calculated for all the ligands investigated in this study at the same B3LYP/6-31G(d,p) (The BASIS line specifies the 6-31G basis set plus one set of d polarisation functions on C and P atoms and one set of p functions on H atoms) level of theory in Gaussian 09, as was done by Suresh and Koga.⁴⁹ In **Table 3.8**, the calculated values are shown. The values calculated for PCy₃ and PPh₃ compared well with those of Suresh and Koga.⁴⁹ It was decided to also calculate the $V_{\min}$ values in Materials Studio since the rest of the results were generated with this software package. Minenkov *et al.*³² showed that the B3LYP functional does not provide very reliable results when the calculated dissociation energies of **A1** and **A2** are compared with the literature determined values. This served as an additional motivation to also calculate the $V_{\min}$ values with Materials Studio. In **Figure 3.19**, a typical visual representation of a generated MESP isosurface is shown. The purple dummy atom indicates the position of the $V_{\min}$ in the MESP isosurface.

Table 3.8 The calculated $V_{\min}$ values for all the ligands investigated in this study

Ligand	Suresh ⁴⁹ (kJ.mol ⁻¹)	Calculated ^a (kJ.mol ⁻¹)	Calculated ^b (kJ.mol ⁻¹)
NHC		-412.56	-246.56
Z-select NHC		-376.32	-232.30
PCy ₃	-188.24	-186.15	-142.71
Phobane		-180.21	-139.14
tBCyP_a		-172.03	-134.30
tBCyP_b		-171.77	-133.08
MeCyP_a		-169.28	-129.63
iPCyP_b		-169.10	-129.74
MeCyP_b		-169.05	-130.89
iPCyP_a		-168.76	-130.54
tBphP_b		-155.23	-120.32
tBphP_a		-154.25	-120.52
iPPhP_a		-152.80	-119.55
MePh_b		-152.75	-118.40
MePh_a		-152.60	-118.25
iPPhP_b		-152.36	-118.97
PPh ₃	-145.81	-143.39	-106.74
P(OCH ₂ CCl ₃) ₃	-26.36	-32.45	-9.99

^a B3LYP/6-31G(d,p), – Gaussian.

^b DMol³ GGA/PW91/DNP – Materials Studio.

In **Table 3.8**, it can be seen that on average there is an energy difference of roughly 37 kJ.mol⁻¹ between the calculated values when using Gaussian and those when using Materials Studio. Consultation with the manufacturers of Materials Studio revealed that this difference should be expected since there are fundamental differences between the functionals and basis sets used in Materials Studio and those used in Gaussian.⁵¹ The much larger energy difference between the calculated values for the NHC-ligand of 166 kJ.mol⁻¹ might be an indication that this method is not

suitable to compare these two different ligand classes with each other. Giering *et al.*⁵² already pointed out that this was a shortcoming of the current approach. Nonetheless, since the purpose of using this method was to identify a poor electron donor and not to evaluate the merit of comparing different ligand classes, the rest of the discussion will focus on this. It is also apparent from **Table 3.8** that the new Cy ligands have a very similar donating ability regardless of the change in functional group; the same is true for the Ph ligands.

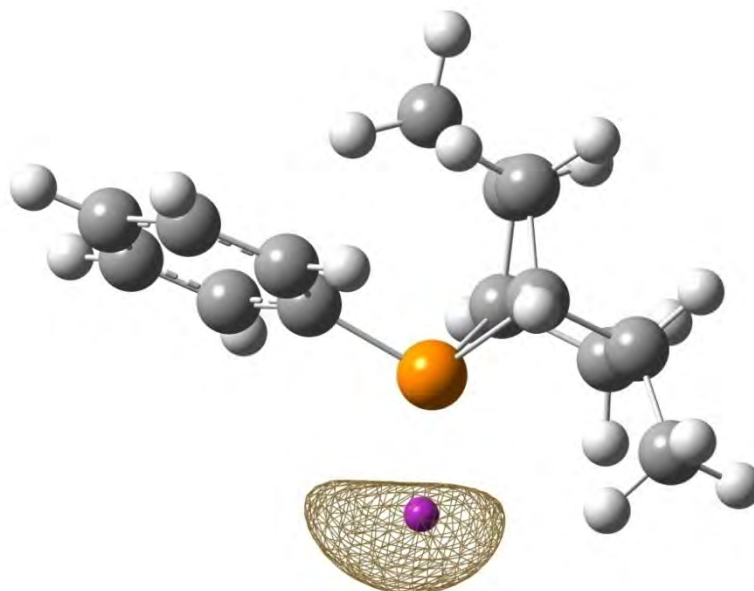


Figure 3.19 A typical visual representation of the $V_{\min}$ in the MESP isosurface.

From **Table 3.8**, and the work of Suresh and Koga,⁴⁹ it was decided to investigate the ligand $\text{P}(\text{OCH}_2\text{CCl}_3)_3$ since it was the poorest donor of those investigated. The very poor donating ability of $\text{P}(\text{OCH}_2\text{CCl}_3)_3$ is evident from both the Gaussian and Materials Studio results. Therefore, our criterion of an extremely poor donor was satisfied. In **Figure 3.20**, the new precatalyst **A106** that will be investigated is shown.

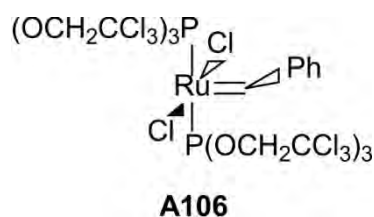


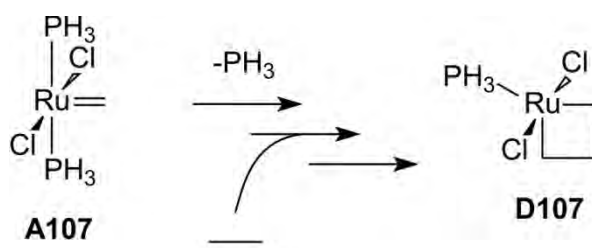
Figure 3.20 The new precatalyst **A106**.

The results of the molecular modelling investigation of **A106** are illustrated in **Figures 3.16** to **3.18**. From **Figure 3.6**, it is known that metathesis activity becomes difficult to nearly impossible for the methyldiene of **A2** when the coordination energy of the alkene has a value of slightly more than 100 kJ.mol^{-1} . From **Figure 3.16**, it can be seen that the coordination energy of 1-octene to **A106** (step **C**) is $71.39 \text{ kJ.mol}^{-1}$, that is 25 kJ.mol^{-1} higher than the coordination energy of 1-octene to **A3**. What immediately captures the eye is the very high energy value of $127.96 \text{ kJ.mol}^{-1}$ for the metallacyclobutane ring, **D**. This is an energy value higher by almost 50 kJ.mol^{-1} than that of **A105**, which is known to be a poor catalyst. This is an indication that activation of this catalyst might be extremely difficult to impossible.

In **Figures 3.17** and **3.18**, it can be seen that in the catalytic cycle the energy values of the metallacyclobutane rings (steps **H** and **M**) are once again much higher than the rest of the steps. This confirms that cross-metathesis of 1-octene with this catalyst might be extremely difficult to impossible. The rate limiting step for the catalytic cycle of **A106** is the formation of the metallacyclobutane ring, **H**; for all the other precatalysts investigated in this study the methyldiene formation step, **J**, is the rate limiting step. The criterion for investigating this new precatalyst was that the ligand had to yield a very poor catalyst. It is clear that this is potentially the case. If the energy trends of **A105** and **A106** are compared (**Figures 3.16** to **3.18**), it becomes clear that the trend of **A105** correlates better with **A106** than with **A1** to **A3**. In **Figure 3.17**, it can be seen that **A2**, which has the longest lifetime of the catalysts investigated, has the lowest metallacyclobutane ring energies. The poor catalysts **A105** and **A106** have the highest metallacyclobutane ring energies. Whether better stabilisation of the metallacyclobutane ring leads to a more stable catalyst and therefore a longer lifetime for the catalyst remains to be seen. Whether this is a major contribution to the lifetime of the catalyst is also still unclear at this point in time.

Caution should be used when interpreting the results of **A106** in **Figures 3.16** and **3.17**, specifically when the energy values of precatalyst **A103** are compared to those of **A106**. Once again, a precatalyst known to be active from literature⁴⁵ has energy values that are higher in several steps than that of the known low activity catalyst **A105** and the predicted poor catalyst **A106**. This once again raises questions about the driving force behind the metathesis reaction. The metallacyclobutane rings of **A103** are not really that much lower in energy than the rest of the activation and catalytic steps. It also seems as if the cut-off value where below or above successful metathesis can take place is not easily discernable. It would seem as if it should be determined on a case-by-case basis. It is also likely that the reason for the inactivity of one catalyst when compared to another has nothing to do with the size of the energy barriers as has already been shown from the results of **A105** in the discussion above.

In a 2004 publication, Suresh and Koga⁵³ investigated the metallacyclobutane ring that would be formed upon the reaction of ethene with **A107** (**D** in **Scheme 3.8**). They determined that a bonding interaction between the orbitals of the $-\text{CH}_2\text{CH}_2\text{CH}_2-$ fragment and the d_{y^2} orbital of the Ru-metal of the metallacyclobutane ring indicated that there is an α -CC agostic interaction present in the complex.⁵³ An α -CC agostic interaction can be described by considering **Figure 3.21**. If the distance indicated by bond 5 is in the same order as that of bonds 1 and 2, and bonds 3 and 4 are elongated (longer than the normal length of a C-C-bond), then there is a chance that the d_{y^2} orbital of the Ru-metal can have an interaction with the orbitals of the carbon directly opposite it. According Suresh and Koga,⁵³ this interaction significantly stabilises the metallacyclobutane ring. They imply that the shorter bond 5 is, the better the stabilisation effect of the metal will be and the energy values of the agostic stabilised metallacyclobutane rings will be lower than the non-agostic types.⁵³ In an effort to investigate the reason for the instability of the metallacyclobutane rings of **A105** and **A106**, it was decided to compare the five bond lengths indicated in **Figure 3.21** to those of **A1** to **A3**, **A103** and **A107** (**Table 3.9**).



Scheme 3.8 The precatalyst **A107** investigated by Suresh and Koga.⁵³

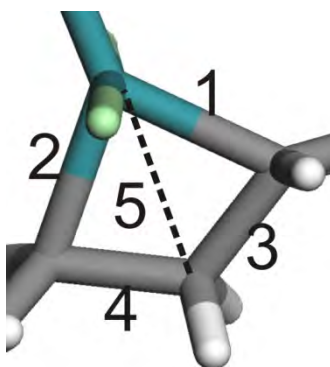


Figure 3.21 The α -CC agostic interaction.

From **Table 3.9**, it can be seen that the less stable metallacyclobutane ring structures, **A105** and **A106**, have slightly shorter bond 5 lengths. For **A103**, the bond 5 lengths of the metallacyclobutane ring structures are fairly similar to those of **A106**, except for **D103**, which has the shortest bond 5 length. This is contrary to what was implied by Suresh and Koga.⁵³ In fact, the

metallacyclobutane ring structures of **A2** that have the lowest energies in **Figure 3.17** and second lowest in **Figure 3.16** have the longest bond 5 length. In **Figure 3.22**, the dissociation and activation steps of **A107** are illustrated. It can be seen that the energy of the metallacyclobutane ring (**D107**) is slightly higher than the coordination energy of the alkene (**C107**). This is a trend that is fairly similar to that observed for **A105** (**Figure 3.16**). The shorter bond 5 length of **D107** in **Table 3.9** can be explained by a slightly unstable metallacyclobutane ring. This once again raises questions about the suitability of using simplified systems to infer properties of the much more complex, non-simplified systems. The fact that all the metallacyclobutane ring structures investigated in this study have nearly identical bond 5 lengths (Seen **Appendix A** for the complete comparison) does suggest that the stabilisation by the α -CC agostic interaction might be nothing more than a structural artefact for the Grubbs-type systems investigated in this study or at best provide a minor contribution to the stabilisation of the metallacyclobutane ring. The reason for the instability of the metallacyclobutane rings of **A105** and **A106** is currently still unclear.

Table 3.9 The calculated metallacyclobutane ring bond lengths of **A1** to **A3**, **A103** and **A105** to **A107**

Step	Bond 1 (Å)	Bond 2 (Å)	Bond 3 (Å)	Bond 4 (Å)	Bond 5 (Å)
D1	2.029	2.050	1.590	1.573	2.263
D2	2.041	2.036	1.582	1.582	2.280
D3	2.028	2.039	1.586	1.581	2.260
D103	2.007	2.071	1.683	1.527	2.232
D105	2.034	2.021	1.588	1.587	2.256
D106	2.054	2.020	1.577	1.595	2.258
D107	1.998	1.998	1.582	1.582	2.255
H1	1.983	2.043	1.583	1.589	2.309
H2	2.020	1.991	1.561	1.618	2.312
H3	2.003	2.018	1.555	1.616	2.292
H103	1.982	2.08	1.653	1.566	2.299
H105	2.019	1.996	1.557	1.619	2.302
H106	1.991	2.027	1.581	1.593	2.297
M1	2.004	2.016	1.557	1.604	2.263
M2	1.991	2.031	1.567	1.593	2.274
M3	2.001	2.023	1.567	1.591	2.259
M103	1.983	2.06	1.652	1.541	2.243
M105	1.993	2.015	1.575	1.594	2.252
M106	1.993	2.022	1.574	1.594	2.247

It is apparent that the lifetime of the catalysts has to be responsible for the higher primary metathesis product (PMP) yield. If the energies of these catalysts are so similar, it stands to reason that the lifetime has to be the answer to why one catalyst is perceived to be more active than

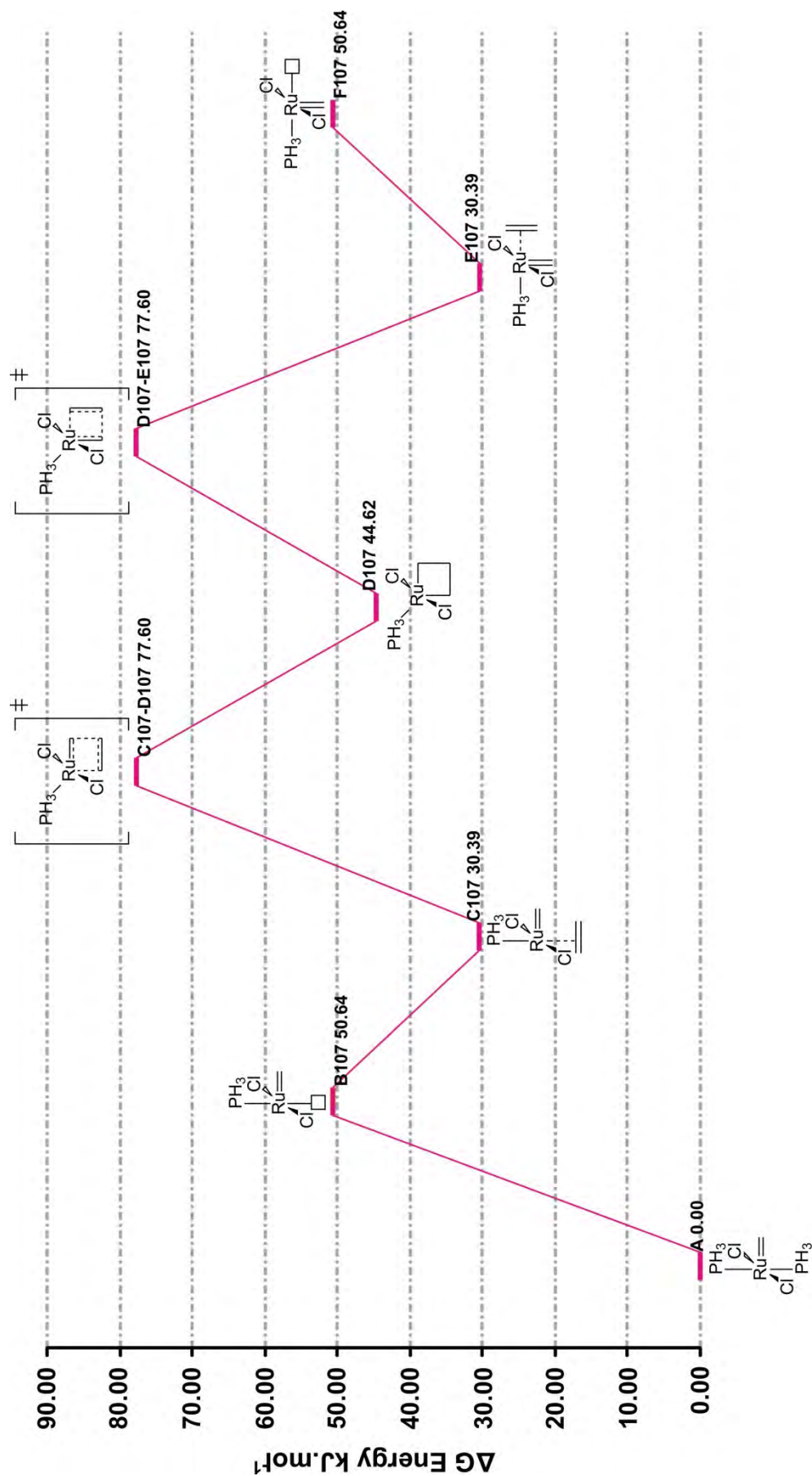


Figure 3.22 The dissociation and activation steps during the redundant metathesis of ethene with A107.

another. The unanswered question that remains is: what is responsible for the improved lifetime of one catalyst when compared to another? As was already seen from the work of Sandford *et al.*,³ the formation of methylenes is very unfavourable. The current piece of work supports this. In all the systems investigated (except **A103** and **A106**), the rate limiting step of the catalytic cycle is the formation of the methylene. The electron donating ability of the ligands on its own does not give a satisfactory answer for the observed energy difference between the various precatalysts. It was decided to investigate the steric influence of these ligands on the metal with the Solid-G program of Guzei *et al.*⁵⁴

3.10 Solid angle steric investigation

For an in-depth explanation of the Solid-G program, the reader can consult the publication where it was first discussed by Guzei *et al.*⁵⁴. To better understand the value of the data obtainable from the Solid-G program,⁵⁴ a shortened explanation of how the data is calculated will be provided.

In 1997, Taverner *et al.*⁵⁵ attempted to quantify ligand-ligand interactions in terms of solid angles. The authors noticed that for iodine the covalent radius was too small and its vdW radius was too large to access steric effects in their system. According to Guzei *et al.*,⁵⁴ this observation revealed an intrinsic flaw that could be generalised to the entire periodic table. According to Brown,⁵⁶ a ligand steric effect is a consequence of non-bonded repulsion between substituents. Interatomic interactions become most attractive when the distance between two atoms corresponds to r_{min} in **Figure 3.23**. As r decreases, the repulsive forces increase rapidly and become predominant at $V(r) = 0$ when the potential energy curve crosses the abscissa at r_z (Z = zero energy point). The non-bonded interactions between two atoms in region I can be well described with a Morse potential,⁵⁷ using the following equation⁵⁸:

$$E_M = \sqrt{E_1^{vdW} E_2^{vdW}} e^{c_{12} - b_{12}r} (e^{c_{12} - b_{12}r} - 2)$$

$$b_{12} = \frac{1}{2}(s_1 + s_2)$$

$$c_{12} = \frac{1}{2}(s_1 r_1 + s_2 r_2)$$

where E_t^{vdW} = non-bonded energy for each atom, r = distance between atoms, r_1 = non-bonded diameter of each atom, s_1 = non-bonded scaling for each atom.⁵⁹

Guzei *et al.*⁵⁴ use atomic radii R_z that correspond to $V(r) = 0$ for all atoms when computing steric parameters. As defined above, the zero point energy radii most closely correspond to the radii of atomic 'hard spheres'. The only exception reported by Guzei *et al.*⁵⁴ was the hydrogen atom for which the computed radius was 1.426 Å, and therefore too large. According to literature, a broad array of hydrogen vdW radii ranging from 0.47⁶⁰ to 1.78⁶¹ Å have been identified. According to

Guzei *et al.*,⁵⁴ atomic vdW radii vary depending on the environment of the atom, and especially on the electronegativity of the atoms they are bound to. Polar flattening results in an anisotropic character of the atom vdW shape; therefore, assigning a radius to the hydrogen sphere was a deliberate compromise by Guzei *et al.*⁵⁴ The smallest reported hydrogen vdW radii are ~ 1.03 Å [neutron diffraction structures of 23 carbohydrates with O–H $\cdots$ O–H $\cdots$ O hydrogen bonds⁶²], 1.02 Å [average of DFT data for seven linear di- and triatomic molecules⁶³], 1.0 Å [neutron diffraction studies⁶⁴], 1.0(1) Å [structural data for “free base”-HX (X = halide) complexes⁶⁵ combined with theoretical results⁶⁰], 0.98 Å [theoretical value for H₂ obtained with questionable assumptions⁶⁶], and 0.47 Å [theoretical studies of complexes formed by HF⁶⁰]. Guzei *et al.*⁵⁴ decided to use the smallest hydrogen vdW radius of 1.0 Å appropriate to the type of their computations instead of the calculated $R_Z(\text{H})$. Guzei *et al.*⁵⁴ reported a complete list of all their calculated R_Z atomic radii.

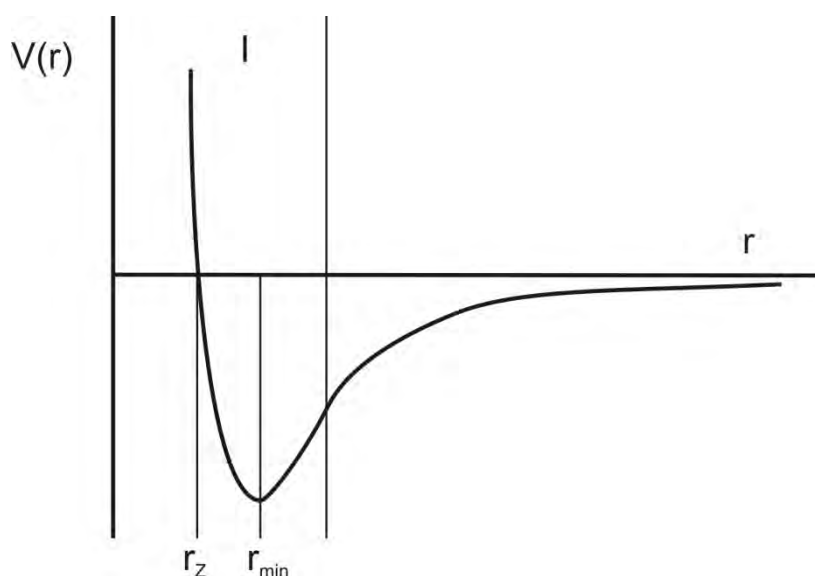


Figure 3.23 Typical interatomic potential with regions to scale. I - the Morse potential region.
 $r_{\min} = \sum_i R_{\min}$, $r_Z = \sum_i R_Z$.

The Solid-G program uses a calculated solid angle, Ω , to calculate a G-parameter that can be used to describe the ligand steric effects as a percentage of the metal coordination sphere shielded by the ligand.⁵⁴ The solid angle, Ω , can be visualised as follows: the central metal of an organometallic complex is replaced with a light source, and each ligand casts a shadow on a sphere surrounding the molecule.⁵⁴ The top row in **Figure 3.24** illustrates this nicely. The figure in the top left corner shows the metal centre (turquoise colour) with the surrounding ligated phosphorous (light purple colour), chlorine (light green colour) and carbon (grey-black colour) atoms. The figure in the top right corner is the space filling model of the one on the left, but in this case the sphere surrounding the molecule is included. The bottom two figures illustrate the same point, but in this case the complete ligands of **A3** were included and not just the ligated atoms.

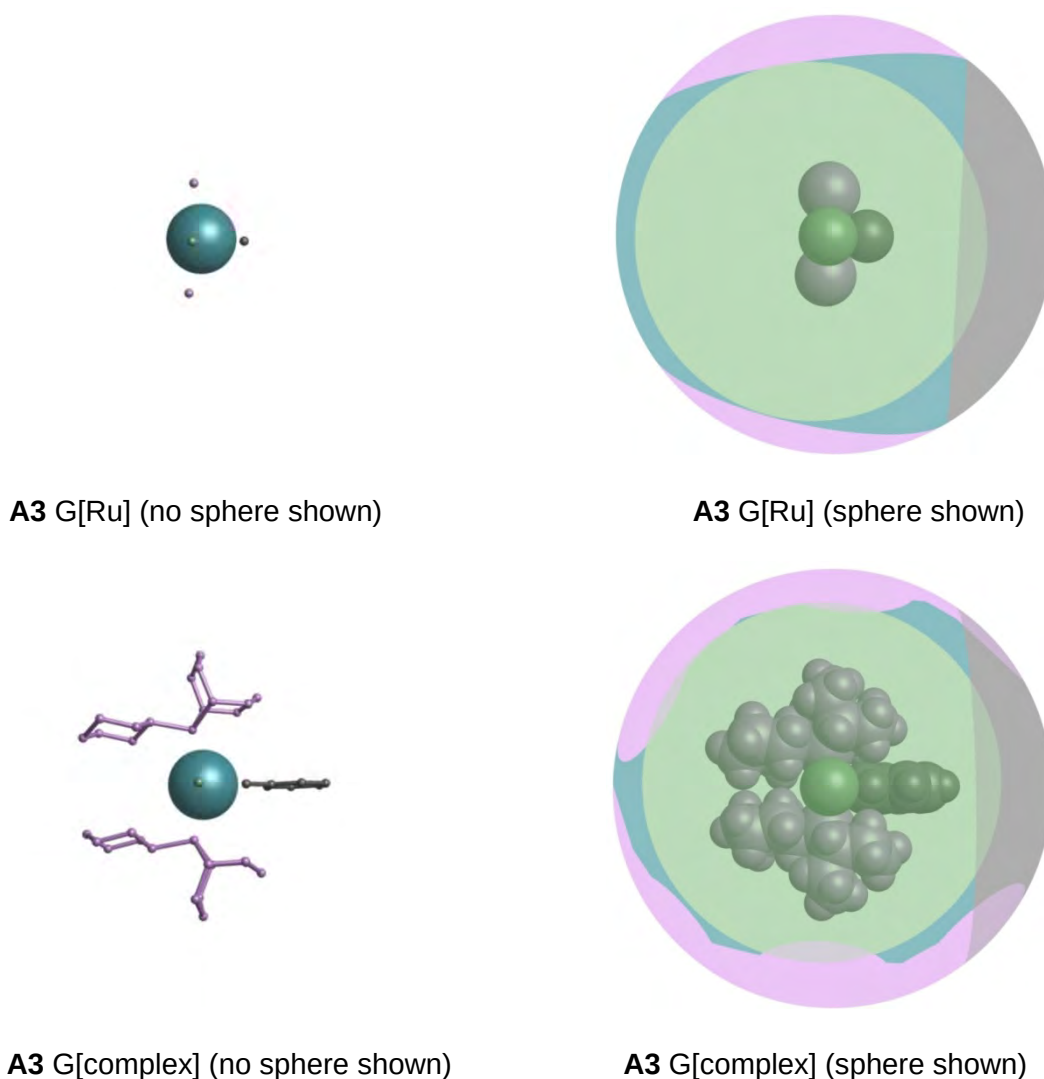


Figure 3.24 An illustration of the ttPhobcat precatalyst (**A3**) % shielded calculated with the Solid Angle program.

The *G*-parameter is entropic in nature and measures the probability of an incoming reagent not accessing the metal centre.⁵⁴ In this study, all the *G*-parameter values are calculated from the theoretical structure data obtained in the sections above. Guzei *et al.*⁵⁴ pointed out the following important aspects:

- The *G*-parameter is expressed in percent, to make it more easily understandable. They argue that it is easier to visualise that five ligands with a *G*-parameter of 20% can theoretically fit around one metal centre, than to decide whether five ligands with identical cone angles of 106.26° can do the same.⁵⁴ While they concede that cone angles may be useful when looking at individual ligands, they go on to point out that estimating the crowdedness of the metal coordination environment becomes complicated when several ligands are considered simultaneously.⁵⁴ They further point out that the maximum cone angle is 360°; but question whether 360 one-degree cone angles or four 90° cone angles will shield the central metal to the same extent. They go on to point out that the solid angle

does not suffer from this ambiguity.⁵⁴ They also point out that certain classes of ligands, such as porphyrins and phthalocyanines cannot be characterised with a meaningful cone angle, but are readily parameterised with Ω and G-parameter values.⁵⁴

- The G-parameter is not dependent on the size, shape, symmetry, or hapticity of the ligand.⁵⁴
- The G-parameter can be calculated for individual ligands or the entire metal complex.⁵⁴
- Atomic R_z radii are used for all G-parameter calculations and not vdW radii.⁵⁴

A typical extract from the output file containing the relevant important data is illustrated in **Table 3.10**.

Table 3.10 Typical Solid-G output data

Ligand #	Omega[L] (Steradians)	G[L] (%)	Equivalent Cone Angle [ECA] (°)				
1	2.89	23.01	114.67				
2	1.52	12.09	81.38				
3	1.51	12.02	81.13				
4	3.64	28.95	130.21				
5	3.54	28.15	128.18				
SUM[G[L]]	13.10	104.22					
G[complex]	11.85	94.31					
G[gamma]	1.25	9.91					
G[Ru1]	9.51	75.71	C1	Cl1	Cl2	P1	P2

Ligand = Ligand #.

Omega[L] = Solid Angle of the ligand.

G[L] = The percentage of the sphere shielded by the ligand.

ECA = Cone angle corresponding to the Omega[L] and not Tolman's cone angle for the ligand. The ECA is always smaller than Tolman's cone angle since this program does not assume free rotation about the M-L axis.

SUM[G[L]] = The sum of all individual ligand G[L] values.

G[complex] = The G value for the complex, all ligands treated as one.

G[gamma] = The percentage of the sphere shielded by more than one ligand.

G[Ru1] = The percentage of Ru1 's surface shielded by the ligated atoms only.

In **Table 3.10**, the SUM[G[L]] value is 104.22%. Some regions are shielded by more than one ligand. This will cause an overestimation of the overall shielding and SUM[G[L]] has to be corrected to find a realistic overall shielding, the G[gamma] value of 9.91% has to be subtracted to give the G[complex] value of 94.31%. **Figure 3.24** illustrates this very nicely. It can clearly be seen in the figure on the bottom right side that there are areas where the shadows cast by the ligands

on the sphere surrounding the complex overlap. This area of overlap corresponds with the G[gamma] values in the various output files. The last important piece of data that can be used from these output files is the G[Ru1] values. In **Figure 3.24**, the two top figures illustrate the G[Ru1] values. In these figures, only the atoms bonded directly to the metal atom are shown.

To evaluate the validity of the data obtainable from the Solid-G program when using the molecular modelling structures, the crystallographic data for **A1**, **A2**, **A101** and **A103** (as was already mentioned previously no XRD-data for **A3** exists) were compared (**Table 3.11**). Only the G[complex] and G[Ru1] values will be compared from this point on since they have the most relevance to the rest of this discussion. As was already mentioned in § 3.5, the molecular modelling results have slightly over-estimated bond lengths when compared to the crystallographic data. The shorter bond lengths explain small differences observed in the G values. The closer the ligated atoms are to the metal centre, the better it will be shielded by these atoms. From **Table 3.11**, this difference is clear. The differences between the molecular modelling and crystallographic determined values are roughly 4% for the ligated atoms (G[Ru1]) and approximately 2% for the complete precatalysts G[complex]. This small discrepancy shows that using the proposed approach will provide acceptable values for the purposes of the current study.

Table 3.11 A comparison between the crystallographic and molecular modelling G[complex] and G[Ru1] values of **A1**, **A2**, **A3** and **A101**

Precatalyst	G[complex] (%)	G[Ru1] (%)
A1 ^{67,a}	96.55	79.51
A1 ^b	94.31	75.71
A2 ^{28,a}	97.61	78.98
A2 ^b	95.12	74.87
A101 ^{30,a}	94.97	80.62
A3 ^b	93.66	76.94
A103 ^{45,a}	93.68	85.59
A103 ^b	91.80	81.58

^a Calculated using crystallographic data.

^b Calculated using molecular modelling data.

Molecular modelling provides an opportunity to investigate the changes in the percentage of the metal shielded during the whole catalytic cycle. The Cartesian coordinates of the atoms in the molecules can be used to determine the G[complex] and G[Ru1] values for all the steps of the reaction scheme of all the precatalysts investigated in the sections above. These values can then be used to determine whether there is any correlation between the % shielded and the observed variance in energies. **Figure 3.25** shows the G[complex] (solid line) and G[Ru1] (dashed line) values for the complete metathesis cycle of all the precatalysts with 1-octene. It was decided to

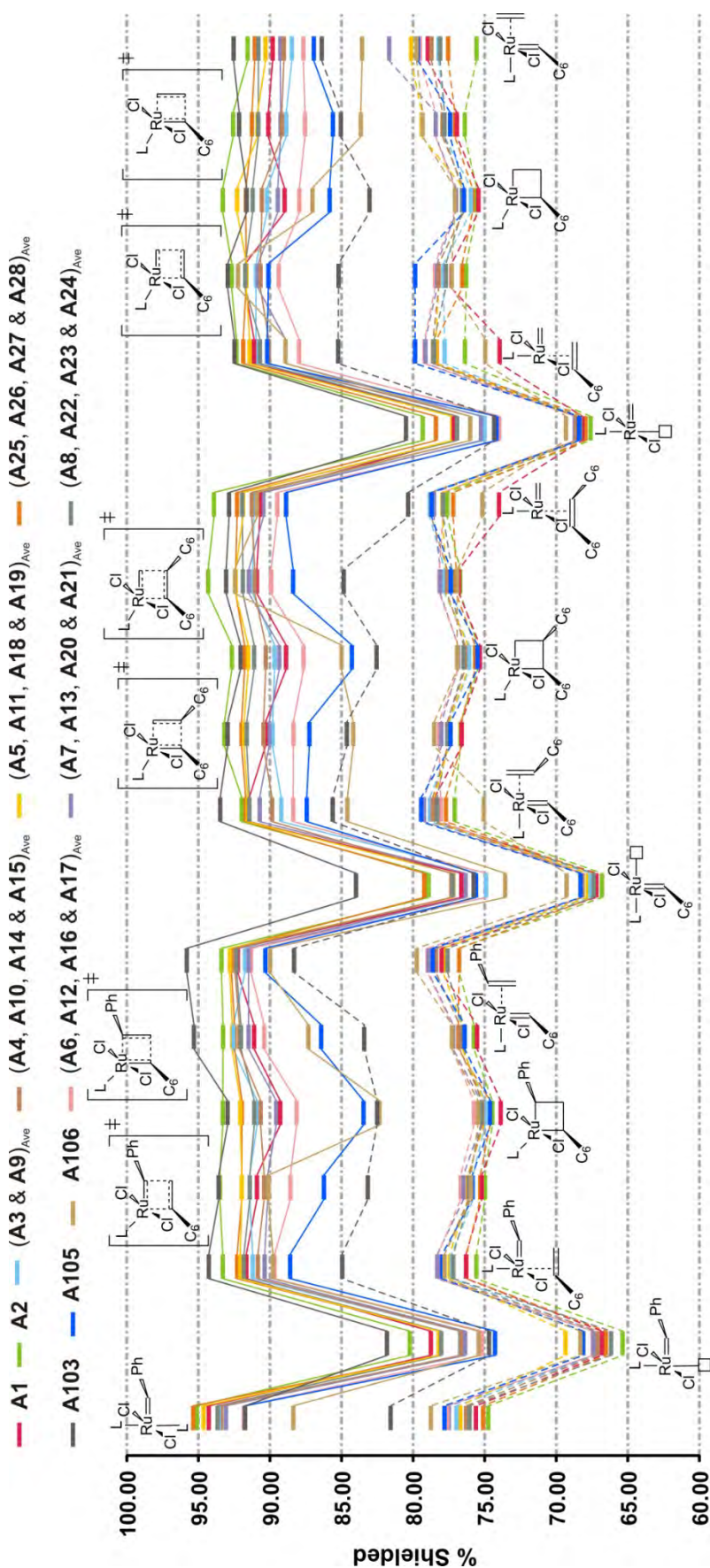


Figure 3.25 A comparison between the G[Complex] (solid line) and G[Ru] (dashed line) values of **A1**, **A2**, **A103**, **A105**, **A106** and the average calculated for the rotational isomers of **A3** to **A28**.

use the average of the values where there is a possibility of rotational isomers (precatalysts **A3** to **A28**). The complete datasets can be found in **Appendix A**.

What immediately becomes apparent when looking at **Figure 3.25** is the similarity between the calculated $G[\text{complex}]$ and $G[\text{Ru1}]$ values of the various catalysts investigated. In fact, in both cases, most of the values for the various steps investigated lie in a narrow band of roughly 5%. This observation shows that the metal remains highly shielded throughout the reaction, except when there is an open coordination site (steps **B**, **F** and **J**). The $G[\text{complex}]$ values of **A103**, **A105** and **A106** are the exception. For **A105** and **A106**, their metallacyclobutane rings of steps **D** and **H** show that the metal is approximately 5% poorer shielded than those of the rest of the catalysts. The metal in the metallacyclobutane rings of **A105** and **A106** for step **M** is also less shielded than the corresponding step of the rest of the catalysts. From **Figure 3.25**, it is clear that there is a slightly larger variance between the catalysts for all the methyldene catalysis steps (**K** to **N**). While it might be thought that the lower % shielded values obtained for **A105** and **A106** are an indication that a poorer shielded metal centre is a contributing factor to the higher energies that are observed in all the methyldene catalysis steps, this theory fails when **A103** is taken into consideration. When the shielding of the metal atom in **A103** is investigated, it is immediately apparent that the extra atom bonded to the metal raises all the $G[\text{Ru1}]$ values by more than 10% in almost all instances. Interestingly enough, the $G[\text{complex}]$ values are fairly similar to that of **A2**. Whether this means that the metal can never be truly 100% shielded cannot be confirmed until a much larger set of precatalysts are investigated. What the % shielded values of **A103** does confirm is that there does not seem to be any correlation with the variance in energies observed in the sections above.

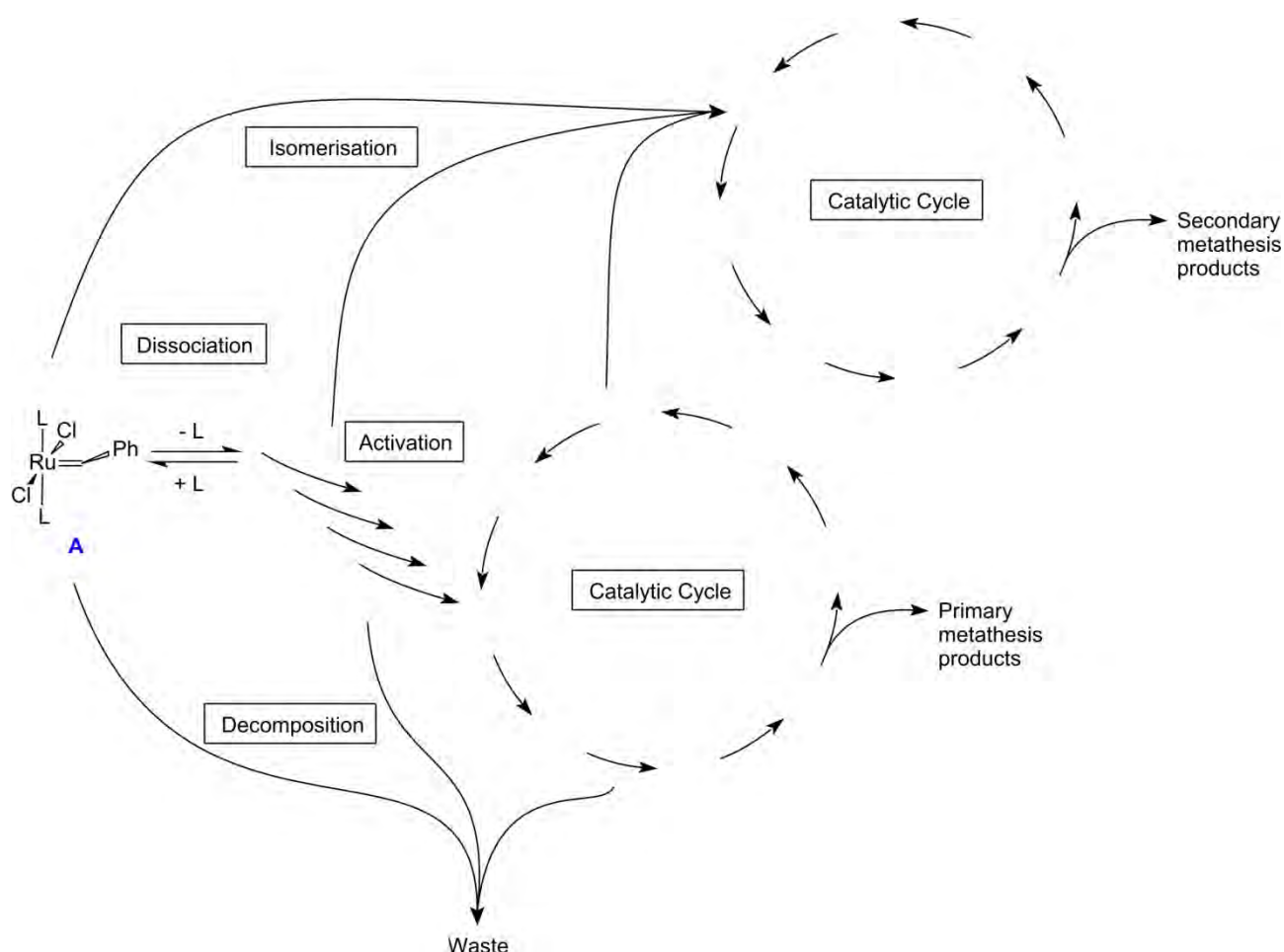
What is also very interesting from the $G[\text{Ru1}]$ values is that the ligated atoms alone shield the metal by between 74 and 80%, except when there is an open coordination site. This would suggest that changing the electronic nature of these atoms should have a much larger effect on the metal than changing a functional group at a point far from the metal. It also makes one wonder whether changing functional groups on the ligand far away from the active point of catalysis can have a direct effect on the metal. While there is no denying that the ligands can have an effect on each other, the real effect of increasing the steric bulk of ligands on the metal has to be investigated in more detail. From **Figure 3.25**, there is no clear evidence that the bigger ligands are always able to better shield the metal.

3.11 Summary

If this steric investigation results are taken along with the molecular modelling results above, where there was also, in most cases, not a large difference between the energies for the various reaction steps, it becomes clear that the property or properties responsible for the observed differences

between the various catalysts are not so easy to determine. **Scheme 3.9** illustrates the shortcomings of all the attempts to date to elucidate the metathesis mechanism by using theoretical methods. Experimentally, the combined rates of all the steps are measured to determine the overall rate of product formation. The rate at which the catalyst decomposes, either during the activation steps or the catalytic cycle or before or during ligand dissociation, is not measured. The rate at which isomerisation and secondary metathesis takes place is also very difficult to separate from the overall reaction rate. During theoretical studies, the focus is also on determining the rate limiting step, but mainly only of the primary metathesis pathway. The decomposition, isomerisation and secondary metathesis pathways are largely ignored. The problem with this approach is that the difference between the catalysts might not lie mainly in the rate of primary metathesis. When investigating different catalyst systems, it also has to be kept in mind that the rate determining step might not be the same for all systems under investigation. It is further evident that using a single simplistic property or a simplified system to try to explain the complex intricacies of these metathesis catalysts is nothing more than folly. It would seem that the most important difference between the catalysts has to lie in the lifetime of the catalysts during metathesis reactions. This means the deactivation mechanism has to be investigated in more detail. Unfortunately, the deactivation mechanism is still very poorly understood.

Several authors have reported the formation of hydrides,^{13,68-73} but the mechanism of how these hydrides are formed is still not understood. Although Janse van Rensburg *et al.*¹³ used theoretical studies to investigate the decomposition behaviour of the methylenes of the **A1**, **A2** and **A3** catalysts with ethene as the substrate, there is still uncertainty as to whether this is the only deactivation pathway. Until the factors responsible for deactivation are better understood, the development of better precatalysts will have to continue to rely on the current serendipitous approach of synthesising a whole library of new ligands and hoping one or more of them show improved metathesis activity. It would also be worthwhile for future studies to look at the catalytic steps that lead to the formation of the experimentally observed isomerisation and secondary metathesis products. The second possibility for future study is to investigate the influence of the solvent on the complete catalyst mechanism. The current study proved that our understanding of the inner workings of the catalyst during the complete catalytic cycle is at this point in time still very poor. If a deeper understanding of the activity of the Grubbs-type precatalysts is to be obtained, no stone should be left unturned.



Scheme 3.9 The shortcomings of all the attempts to date to elucidate the metathesis mechanism by using theoretical methods.

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