Notes on Intuitionistic Fuzzy Sets
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Evaluating the performance of catalyst and feedstocks in the fluid catalytic cracking process: Application of InterCriteria Analysis with weight coefficients of the objects

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Abstract: In the current investigation an evaluation of the performance of catalyst and feedstocks in the fluid catalytic cracking process is proposed. An application of the newly modified method

of InterCriteria Analysis—with weight coefficients of the objects—is performed. The obtained results are discussed in the light of a comparison with the standard ICrA.
Keywords: Intercriteria analysis, Index matrix, Intuitionistic fuzzy set, Fluid catalytic cracking.
2020 Mathematics Subject Classification: 03E72.

1 Introduction

The fluid catalytic cracking (FCC) is a major conversion process applied in modern petroleum refining [10]. Since its introduction in 1942 with the initial aim to deliver high octane gasoline it has undergone substantial development due to its flexibility to process low value heavy oils and convert them into high value transportation fuels and light olefins, feed for the petrochemical industry, with a substantial variation in product slate depending on market demand [7, 12, 16]. Along with the vacuum residue hydrocracking the FCC is considered the most profitable process in modern petroleum refining [16]. Any improvement in the performance of the FCC unit has a considerable impact on the refinery profitability [14]. This can explain why so many attempts have been made by the researchers working in the field of petroleum processing to look for effective low cost methods to improve performance of the FCC process [16]. Such a low cost method has been identified to be the use of activating additives added to the feed of the FCC process [19]. This approach has been based on "the adjustable phase transition theory". The mechanism of FCC feed activating additives action has been explained on the base of colloid structure mechanism [19]. This mechanism was developed by the use of the theoretical basis put forward by the former Soviet Union researchers [19]; a Doctor of Sciences thesis and several PhD theses were defended on this subject [11, 20].

Most of the studies dedicated to the FCC process intensification by the use of activating additives were carried out in laboratory catalytic cracking units with unknown or not reported repeatability and reproducibility. For example, Wang reported that the error of domestic experimental results was large, and the reliability of the results was questionable. The application of oxygen containing additives to activate FCC feed reported in the PhD thesis of Zvyagin tested in a standardized micro activity (MAT) FCC unit operating under the standards ASTM D 3907, and ASTM D 5154 showed variations in FCC yields within the uncertainty of the measurement. These results put under question the efficiency of the activating additive action.

In order to examine whether the application of “the adjustable phase transition theory” belongs to the so called “zombie ideas” well described by Gray [9] MAT FCC tests with vacuum gas oil activated by addition of 2% FCC slurry oil (SLO) and not activated on two different catalysts were performed. The MAT tests were carried out at reaction temperature of 527°C, catalyst time on stream of 30 seconds and variation of catalyst-to-oil ratio between 1 and 6 wt./wt. The FCC performance for the two catalysts with the two feeds activated, and not activated (total four cases) was compared at constant conversion of 65 wt.%, and at constant yield of coke of 1.9 wt.% obtained by interpolation of the selectivity curves as described in [17, 18].

Considering the successful application of intercriteria analysis (ICrA) to evaluate petroleum processing data to assess the extent of similarity between crude oils [13], and vacuum residues [15] a decision was made to apply ICrA with weight coefficients to the FCC data from the four cases mentioned above. The aim of this study is to evaluate the extent of similarity between the yield structure, gasoline octane, and gasoline hydrocarbon composition at constant conversion of 65%, and at constant coke of 1.9 wt.% for the two different catalysts that have cracked a straight run vacuum gas oil derived from Urals crude oil and a blend of it with FCC slurry oil in a laboratory MAT unit operating under requirements of the standards ASTM D 3907, and ASTM D 5154.

ICrA is a decision making method [5] based on the theories of intuitionistic fuzzy sets [1, 3] and index matrices [2]. The proposed approach compares multiple objects according to multiple criteria using one iteration. The input dataset is presented in the form of index matrix. Criteria are placed on the rows. Objects are written on the columns. The data can be presented in different form: real numbers, intuitionistic fuzzy pairs, (0, 1) variables and etc. ICrA compares the relations by pairs. If the two pairs have the same sign the degree of membership is increased. If the two pairs do not have the same sign the degree of non-membership is increased. If the pairs have the sign "=" the degree of uncertainty is increased. Survey on the theory and applications of the ICrA is presented in [4, 8]. The last extension of ICrA is called "InterCriteria Analysis with Weight Coefficients of Objects or Criteria" [6]. In this approach the ICrA calculates the nearness between the criteria and the nearness between the objects. The weights are assigned to every object. The comparisons between the objects/criteria and calculations of the intuitionistic fuzzy pairs includes the weights information. The results are determined using the following scale:

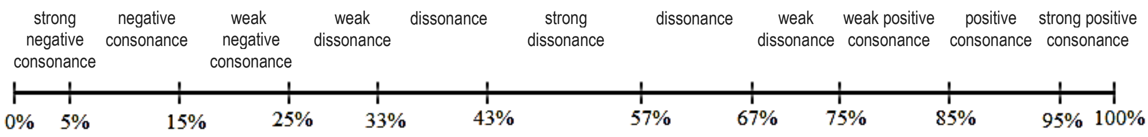

Figure 1. Scale for determination of the type of the correlations between the criteria

When the degree of membership is near to 1.0 then the compared criteria are similar. When the degree of membership is near to 0.0 then the compared criteria are opposite. When the degree of membership is in the interval [0.25, 0.67], then the compared criteria are independent. These three cases are called positive consonance (strong positive consonance, positive consonance, weak positive consonance), negative consonance (strong negative consonance, negative consonance, weak negative consonance) and dissonance (strong dissonance, dissonance, weak dissonance).

2 Results and discussions

In the current investigation InterCriteria Analysis with Weight Coefficients is applied to the datasets for feedstocks. The obtained results are compared with the results from the Standard ICrA applications, and discussed.

2.1 Application of InterCriteria Analysis with weight coefficients of the objects and standard ICrA over normalized data for constant conv. (65)

First application of the ICrA with weight coefficients of objects is made using the data with weight coefficients of objects in Table 1. The input dataset is normalized using the normalization formula

$$x_{new} = \frac{x - x_{\min}}{x_{\max} - x_{\min}}. \quad (1)$$

Table 1 shows the yield structure, hydrocarbon composition of the obtained gasoline (cracked naphtha = CN), research, and motor octane numbers (RON, and MON respectively), and MON, and RON octane barrels. Two catalysts Futura 70, and equilibrium catalyst sampled from the "LUKOIL Neftohim Burgas" FCC unit designated as E-CAT and two feeds: a straight run vacuum gas oil derived from Urals crude oil, and its blend with 2% FCC SLO were cracked in the MAT FCC unit. The four cases designation is following:

1. FUTURA 70+ = Catalyst Futura 70 (fresh, metal free deactivated) that cracks feed 1 (straight run vacuum gas oil derived from Urals crude oil)
2. FUTURA 70 + 2% SLO = Catalyst Futura 70 (fresh, metal free deactivated) that cracks feed 2 (straight run vacuum gas oil derived from Urals crude oil (98%) mixed with 2% FCC SLO)
3. ECAT = Equilibrium catalyst sampled from "LUKOIL Neftohim Burgas" FCC unit that cracks feed 1 (straight run vacuum gas oil derived from Urals crude oil)
4. E-CAT NEF + 2% SLO = Equilibrium catalyst sampled from "LUKOIL Neftohim Burgas" FCC unit that cracks feed 2 (straight run vacuum gas oil derived from Urals crude oil (98%) mixed with 2% FCC SLO)

Table 1. FCC Yields, hydrocarbon composition, and RON, and MON of cracked naphtha (CN) interpolatated at constant conversion of 65 wt.%.

		Objects	FUTURA 70 + 2% SLO	FUTURA 70+	E-CAT NEF + 2% SLO	ECAT
			P42.157.2	P42.157.1	96301122	96301121
Nr	**Criteria**	**Weight (Objects) ▸ / Weight (Criteria) ▾**	2	1	4	3
1	Conversion at CTO =4	2	0,067	1,000	0,000	0,667
2	CTO	2	0,000	0,000	1,000	0,000
3	Hydrgen	2	0,000	0,014	1,000	0,901
0	Hydrogen/CTO	2	0,000	0,018	0,933	1,000
1	Carbon	3	0,000	0,000	0,667	1,000
2	Δ coke	4	0,000	0,090	0,409	1,000
3	Dry gas	2	0,000	0,000	0,000	1,000
4	C3=	4	0,000	0,000	1,000	0,500
5	C3	1	0,154	0,000	1,000	0,231
6	Total C3	1	0,000	0,000	1,000	0,333
7	i-C4=	5	0,000	0,000	1,000	1,000
8	i-C4	5	0,333	0,000	1,000	0,000

						Contd.
9	n-C4	1	0,286	0,143	1,000	0,000
10	Total C4='s	5	1,000	1,000	1,000	0,000
11	Total C4	3	0,250	0,000	1,000	0,000
12	C3= + C4=	5	0,000	0,000	1,000	0,000
13	LPG	2	0,125	0,000	1,000	0,125
14	LPG Olef.	2	0,765	0,941	0,000	1,000
15	CN	6	1,000	0,929	0,000	0,214
16	LC0 (221-3338°C)	6	0,023	0,023	0,000	1,000
17	HCO (338°C+)	1	0,977	0,977	1,000	0,000
18	CN n-Paraffins	1	0,750	1,000	0,250	0,000
19	CN i-Paraffins	5	1,000	1,000	0,222	0,000
20	CN Aromatics	4	0,667	0,000	1,000	0,833
21	CN Naphthenes	4	0,000	1,000	1,000	1,000
22	CN Olefins	4	0,000	0,158	0,734	1,000
23	GC-MON	7	0,000	0,000	1,000	0,800
24	GC-RON	7	0,111	0,000	1,000	1,000
25	MON octane barrels	7	1,000	1,000	0,000	0,333
26	RON octane barrels	7	1,000	1,000	0,000	0,375

The newly modified method of ICrA with Weight Coefficients of Objects is applied to the dataset presented in Table 1. The relations between the objects are compared using their weight coefficients. The weights of the objects are written additionally to the input data. Thereafter the results of ICrA with Weight Coefficients of Objects will be compared with the results from Standard ICrA.

The results of ICrA with Weight Coefficients of Objects application and Standard ICrA investigation, represented as intuitionistic fuzzy pairs (containing the degree of membership and degree of non-membership), are presented in Table 2.1 and Table 2.2.

Table 2.1 The intuitionistic fuzzy pairs obtained as a result of the application of ICrA with weight coefficients of objects

⟨μ, ν⟩	**FUTURA 70 + 2% SLO**	**FUTURA 70+**	**E-CAT NEF + 2% SLO**	**ECAT**
FUTURA 70 + 2% SLO	⟨1.00, 0.00⟩	⟨0.48, 0.12⟩	⟨0.13, 0.39⟩	⟨0.17, 0.49⟩
FUTURA 70+	⟨0.48, 0.12⟩	⟨1.00, 0.00⟩	⟨0.09, 0.47⟩	⟨0.25, 0.34⟩
E-CAT NEF + 2% SLO	⟨0.13, 0.39⟩	⟨0.09, 0.47⟩	⟨1.00, 0.00⟩	⟨0.23, 0.30⟩
ECAT	⟨0.17, 0.49⟩	⟨0.25, 0.34⟩	⟨0.23, 0.30⟩	⟨1.00, 0.00⟩

Table 2.2 The intuitionistic fuzzy pairs obtained as a result of the Standard ICrA application

$\langle\mu,\nu\rangle$	**FUTURA 70 + 2% SLO**	**FUTURA 70+**	**E-CAT NEF + 2% SLO**	**ECAT**
FUTURA 70 + 2% SLO	⟨1.00, 0.00⟩	⟨0.56, 0.14⟩	⟨0.24, 0.34⟩	⟨0.22, 0.49⟩
FUTURA 70+	⟨0.56, 0.14⟩	⟨1.00, 0.00⟩	⟨0.27, 0.43⟩	⟨0.31, 0.32⟩
E-CAT NEF + 2% SLO	⟨0.24, 0.34⟩	⟨0.27, 0.43⟩	⟨1.00, 0.00⟩	⟨0.23, 0.34⟩
ECAT	⟨0.22, 0.49⟩	⟨0.31, 0.32⟩	⟨0.23, 0.34⟩	⟨1.00, 0.00⟩

Table 3. Comparison of the results of ICrA with weight coefficients of objects and Standard ICrA applications over the dataset

Type of correlations	**Number of pairs of objects**	
	ICrA with Weight Coefficients of Objects	***Standard ICrA***
strong positive consonance [0,95; 1,00]	-	-
positive consonance [0,85; 0,95)	-	-
weak positive consonance [0,75; 0,85)	-	-
weak dissonance [0,67; 0,75)	-	-
dissonance [0,57; 0,67)	-	-
strong dissonance [0,43; 0,57)	1	1
dissonance [0,33; 0,43)	-	-
weak dissonance [0,25; 0,33)	1	2
weak negative consonance [0,15;0,25)	2	3
negative consonance [0,05;0,15)	2	-
strong negative consonance [0,00;0,05)	-	-

The results of ICrA with Weight Coefficients of Objects application are following: 1 pair of objects in strong dissonance, 1 pair of objects in weak dissonance, 2 pairs of objects in weak negative consonance, 2 pairs of objects in negative consonance.

The pairs of objects in strong dissonance have the following form:

- FUTURA 70 + 2% SLO and FUTURA 70+

The pairs of objects in weak dissonance have the following form:

- FUTURA 70+ and ECAT

The pair of objects in strong dissonance and weak dissonance are independent. They do not have determined relationships.

The pairs of objects in weak negative consonance have the following form:

- FUTURA 70 + 2% SLO and E-CAT NEF + 2% SLO
- FUTURA 70 + 2% SLO and ECAT

The pairs of objects in negative consonance have the following form:

- FUTURA 70+ and E-CAT NEF + 2% SLO
- E-CAT NEF + 2% SLO and ECAT

The pairs of objects in negative consonance have opposite behavior. They do not have determined relationships. They have opposite properties.

The results of Standard ICrA are following: 1 pair of objects in strong dissonance, 2 pairs of objects in weak dissonance and 3 pairs of objects in weak negative consonance. In the ICrA with Weight Coefficients of Objects application the pair "FUTURA 70+ and E-CAT NEF + 2% SLO" is in negative consonance while in the Standard ICrA investigation this pair is moved to the area of weak dissonance. The pair "FUTURA 70 + 2% SLO and E-CAT NEF + 2% SLO" is in negative consonance in the ICrA with Weight Coefficients of Objects application and in weak negative consonance in the Standard ICrA testing. The pair "FUTURA 70+ and ECAT" is in dissonance in the ICrA with Weight Coefficients of Objects application and in weak dissonance in the Standard ICrA investigation.

2.2 Applications of InterCriteria Analysis with weight coefficients of the objects and standard ICrA over normalized data for constant coke (1,9)

The second application of the ICrA with Weight Coefficients of Objects is conducted using the data with the weight coefficients of objects in Table 4. The input dataset is normalized using the normalization formula (1).

ICrA with Weight Coefficients of Objects is applied to the dataset presented in Table 4. The relations between the objects are compared using their weight coefficients. The results, represented as intuitionistic fuzzy pairs containing the degree of membership and degree of non-membership, are given in Table 5.1. In the next Table 5.2 are presented the results from the Standard ICrA over the respective dataset.

Table 4. FCC Yields, hydrocarbon composition, and RON, and MON of cracked naphtha (CN) interpolated at constant coke yield of 1.9 wt.%.

		Objects	FUTURA 70 + 2% SLO	FUTURA 7 0+	E-CAT NEF + 2% SLO	ECAT
			P42.157.2	P42.157.1	96301122	96301121
Nr	**Criteria**	**Weight (Objects) ▸ Weight (Criteria) ▾**	1	2	3	4
1	Conversion	5	1,000	0,889	0,221	0,000
2	CTO	1	1,000	0,778	0,445	0,000
3	Hydrgen	2	0,667	0,000	1,000	0,700
4	Dry gas	1	1,000	0,800	0,200	0,000
5	C3=	4	0,025	0,025	1,000	0,000
6	C3	1	1,000	0,733	0,333	0,000
7	Total C3	1	1,000	0,857	0,142	0,000
8	i-C4=	5	1,000	1,000	0,000	0,000
9	i-C4	5	1,000	0,833	0,333	0,000
10	n-C4	1	1,000	0,750	0,250	0,000

11	Total C4='s	5	1,000	0,857	0,143	0,000
12	Total C4	3	1,000	0,846	0,231	0,000
13	C3= + C4=	5	1,000	0,917	0,167	0,000
14	LPG	2	1,000	0,850	0,200	0,000
15	LPG Olef.	2	0,000	0,412	0,412	1,000
16	CN	6	1,000	0,843	0,214	0,000
17	LC0 (221-338°C)	6	1,000	0,833	0,167	0,000
18	HCO (338°C+)	1	0,000	0,157	0,784	1,000
19	CN n-Paraffins	1	1,000	1,000	0,000	0,000
20	CN i-Paraffins	5	1,000	0,992	0,000	0,748
21	CN Aromatics	4	0,286	0,000	0,286	1,000
22	CN Naphthenes	4	0,000	0,364	0,636	1,000
23	CN Olefins	4	0,000	0,286	0,762	1,000
24	GC-MON	7	0,500	0,000	1,000	0,500
25	GC-RON	7	0,000	0,000	1,000	0,600

Table 5.1 The intuitionistic fuzzy pairs obtained as a result of the application of ICrA with weight coefficients of the Objects

$\langle\mu, \nu\rangle$	FUTURA 70 + 2% SLO	FUTURA 7 0+	E-CAT NEF + 2% SLO	ECAT
FUTURA 70 + 2% SLO	⟨1.00, 0.00⟩	⟨0.51, 0.07⟩	⟨0.06, 0.52⟩	⟨0.06, 0.50⟩
FUTURA 7 0+	⟨0.51, 0.07⟩	⟨1.00, 0.00⟩	⟨0.09, 0.82⟩	⟨0.14, 0.46⟩
E-CAT NEF + 2% SLO	⟨0.06, 0.52⟩	⟨0.09, 0.82⟩	⟨1.00, 0.00⟩	⟨0.42, 0.46⟩
ECAT	⟨0.06, 0.50⟩	⟨0.14, 0.46⟩	⟨0.42, 0.46⟩	⟨1.00, 0.00⟩

Table 5.2 The intuitionistic fuzzy pairs obtained as a result of the application of Standard ICrA

$\langle\mu, \nu\rangle$	FUTURA 70 + 2% SLO	FUTURA 7 0+	E-CAT NEF + 2% SLO	ECAT
FUTURA 70 + 2% SLO	⟨1.00, 0.00⟩	⟨0.49, 0.06⟩	⟨0.08, 0.49⟩	⟨0.40, 0.47⟩
FUTURA 70+	⟨0.49, 0.06⟩	⟨1.00, 0.00⟩	⟨0.10, 0.85⟩	⟨0.12, 0.44⟩
E-CAT NEF + 2% SLO	⟨0.08, 0.49⟩	⟨0.10, 0.85⟩	⟨1.00, 0.00⟩	⟨0.42, 0.14⟩
ECAT	⟨0.40, 0.47⟩	⟨0.12, 0.44⟩	⟨0.42, 0.14⟩	⟨1.00, 0.00⟩

The types of correlations are determined according to the scale of Figure 1. The subsequent Table 6 contains the comparison of the results of the ICrA with weight coefficients of objects with the application of the standard ICrA method.

Table 6. Comparison of the results of the ICrA with weight coefficients of objects and the standard ICrA method, applied to the dataset

Type of correlations	**Number of pairs of objects**	
	ICrA with Weight Coefficients of Objects	***Standard ICrA***
strong positive consonance [0,95; 1,00]	**-**	**-**
positive consonance [0,85; 0,95)	**-**	**-**
weak positive consonance [0,75; 0,85)	**-**	**-**
weak dissonance [0,67; 0,75)	**-**	**-**
dissonance [0,57; 0,67)	-	-
strong dissonance [0,43; 0,57)	1	1
dissonance [0,33; 0,43)	1	2
weak dissonance [0,25; 0,33)	-	-
weak negative consonance [0,15;0,25)	**-**	**-**
negative consonance [0,05;0,15)	4	3
strong negative consonance [0,00;0,05)	-	-

The results of ICrA with Weight Coefficients of Objects are following: 1 pair of objects in strong dissonance, 1 pair of objects in dissonance and 4 pairs of objects in negative consonance.

The pairs of objects in strong dissonance have the following form:

- FUTURA 70 + 2% SLO and FUTURA 70+

The pairs of objects in dissonance have the following form:

- E-CAT NEF + 2% SLO and ECAT

The pairs of objects in strong dissonance and dissonance are independent. They do not have determined relationships.

The pairs of objects in negative consonance have the following form:

- FUTURA 70 + 2% SLO and E-CAT NEF + 2% SLO
- FUTURA 70 + and E-CAT NEF + 2% SLO
- FUTURA 70 + and ECAT
- FUTURA 70 + 2% SLO and ECAT

The pairs of objects in negative consonance have opposite behavior. They do not have determined relationships. They have opposite properties.

The results of Standard ICrA are following: 1 pair of objects in strong dissonance, 2 pairs of objects in dissonance and 3 pairs of objects in negative consonance. The results are similar with the results of the of ICrA with Weight Coefficients of Objects except for the pair "FUTURA 70 + 2% SLO and ECAT". In the application of ICrA with Weight Coefficients of Objects this pair is in negative consonance while in the Standard ICrA investigative the pair is moved to the area of dissonance. The obtained results are presented in the Intuitionistic Fuzzy Triangle (Figure 2).

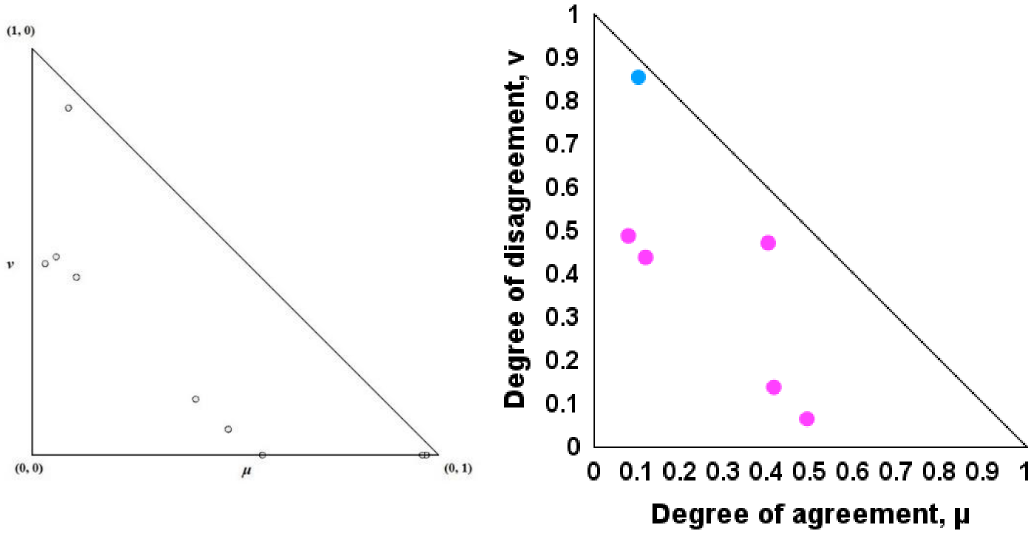

Figure 2. Obtained results, presented in Intuitionistic Fuzzy Triangle: left – the results of ICrA with Weight Coefficients of Objects; right – the results from Standard ICrA

The objects from the input datasets used in the presented ICrA applications are determined are correct and independent. They are in the area of dissonance (weak dissonance, dissonance and strong dissonance) and negative consonance (weak negative consonance, negative consonance and strong negative consonance). The objects in the field of dissonance are mostly independent while the objects in the area of negative consonance even have opposite behavior.

3 Conclusion

In the current investigation an evaluation of the performance of two feedstocks: 1) straight run vacuum gas oil derived from Urals crude oil, and 2) its activated blend with a 2% FCC slurry oil, cracked on two different FCC catalysts by InterCriteria analysis with weight coefficients was proposed. The results of ICrA evaluation showed that the comparison of the two feeds with the two catalysts carried out on the base of the interpolated yields at constant conversion of 65% (Case 1), and at constant coke of 1.9% (Case 2) that in both cases dissonance exists between both feeds (activated with 2% FCC SLO one, and non-activated vacuum gas oil) cracked on the catalyst Futura 70, and the equilibrium commercial catalyst. The dissonance with the catalyst Futura 70 was strong, while that with the equilibrium commercial catalyst was weak. This suggests that the difference in yield structure characterized by the weight coefficients between the activated and the non-activated feed is substantial. Therefore, a conclusion could be made based on the ICrA evaluation with weight coefficients of the objects that the activation of a FCC feed with 2% slurry oil may lead to a statistically meaningful variation of yields and product quality.

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