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An approach based on Rough Sets Theory and Grey System for Implementation of Rule-Based Control for Sustainability of Rotary Clinker Kiln

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Abstract

Fault diagnosis is an important issue for many engineering applications. It is always of a great importance to have an early fault detection and diagnosis to avoid its progression. Different methods and approaches were developed earlier for fault detection and diagnosis. These methods employ different approaches ranging from statistical techniques to artificial intelligence. This paper proposes a hybrid approach based on rough set theory and grey system to extract the hidden relations and implement rule-Based Control for Sustainability of rotary clinker kiln. To show the effectiveness of the proposed approach, a comparison was made with the previous literature .The results show that the proposed approach can remedy the defects of the other methods.

Keywords: Rough Sets, Grey theory, Attribute reduction, Data Mining, Fault Diagnosis; Clinker Rotary Kiln.

1. INTRODUCTION

Mechanical machines fault diagnosis can be defined as the ability to detect fault, isolate failed component and take the decision concerning the failed component on the system health. No doubt that early detection of faults and diagnosis is a very costly process, so in most plants only the critical parts of the machine whose failures will make a big problem and may cause the breakdown are frequently examined. There are many studies which its main goal is to diagnosis faults [1, 2, 3, 4, 5] considering the human operator control is the main base. Recently, in many control systems the human operator control is not satisfactory so many computer control systems are appeared and many engineers and scientists focused their efforts to improve these systems which needs some expert's decision process. It's worth noting that Most of the recently used techniques required expensive equipment or accurate mathematical models, which are challenging issues.

Nowadays, Rough set theory (RST) has been used as a mathematical tool to analyze various types of imprecise and uncertain data. It was used in many applications as tool for feature selection and rule extraction. Also Rough set theory has the ability to combine with another technique to extract decision rules. For more details see [6-16]. Grey system theory also has the ability to extract a model from the data by reducing the precision of data expression [17,18]. In this research both theories (grey system and rough set theory) were combined to discover grade rules of Fault Diagnosis of Mechanical Machines and to implement rule-based control of rotary clinker kiln.

2. THEORETICAL BACKGROUND

2.1 Basic concepts of RST

RST was proposed by Pawlak (1982) and it is consider as powerful mathematical tool for reasoning about imprecision and uncertainty [10]. Its philosophy is based on the idea of classification. The definitions of information function, indiscernibility relation, lower and upper approximation, accuracy of the approximation can be summarized as follow:

- Formally, a data table is the 4-tuple $S = \langle U, Q, V, f \rangle$, where U a finite set of objects (universe), $Q = \{q_1, q_2, q_3 \ldots\ldots q_m\}$ is a finite set of attributes, Vq is the domain of the attribute q, $V = \bigcup_{q \in Q} V_q$ and $f:$ UxQ $\rightarrow$ V is a total function such that $f(x, q) \in V_q$ for each $q \in Q, x \in U$, called information function.
- an indiscernibility relation on U, denoted by IP:

$$I_p = \{(x,y) \in UxU : f(x,q) = f(y,q) \forall q \in P\} \tag{1}$$

- Let X a non-empty subset of U and $\phi \neq P \subseteq Q$ then The P-lower approximation and the P-upper approximation of X in S as shown in figure 1 are defined, respectively, as:

$$\underline{P}(X) = \{x \in U : I_P(x) \subseteq X\} \tag{2}$$

$$\overline{P}(X) = \bigcup_{x \in X} I_P(X) \tag{3}$$

- accuracy of the approximation of X can be defined as :

$$\alpha_P(X) = \frac{|\underline{P}(X)|}{|\overline{P}(X)|} \tag{4}$$

- The set containing all the indispensable attributes of P is known as the core.

$$Core_{\gamma}(P) = \bigcap \operatorname{Re} d_{\gamma}(P) \tag{5}$$

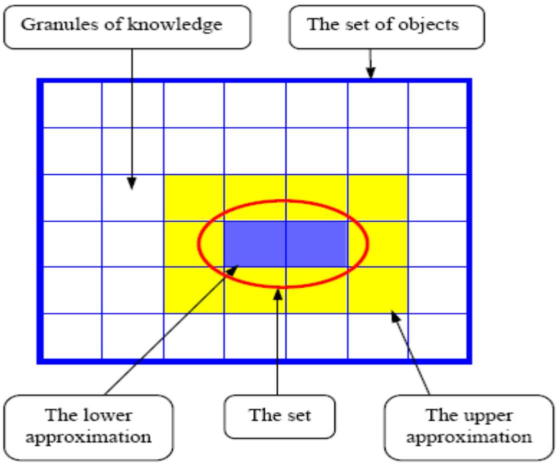

Figure 1. The graphical illustration of the set approximations

2.2 Basic concepts of Grey System Theory

Grey system theory proposed by Professor Julong Deng the famous Chinese scholar. Its main goal is to discover the mathematical relationship and extracting rules among some attributes or single attribute based on the behavior feature data. It has many applications in different fields such as social, economic, ecological system. Grey number is considered as the basic cell of grey system, it can be defined as it is a number whose the range of its value lies is known but the exact value is unknown [9, 10]. Based on the given information a whitening weight function was designed and used to whiten the grey number. A whitening weight function can be defined as it is the continuous functions with fixed starting and ending points, and values increasing on the left and decreasing on the right as shown in Fig 2. It is important to note that there are many patterns for the whitening weight function a typical weight function of whitenization f [a1, b1, b2, a2] is shown in Figure 2.

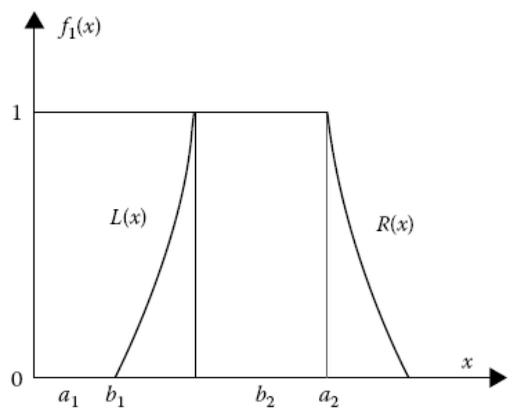

Figure 2. Weight functions of whitenization

Grey degree g° of the grey number x can be defined as:

$$g^{o} = \frac{2|b_1 - b_2|}{b_1 + b_2} + \max\left\{\frac{|a_1 - b_1|}{b_1}, \frac{|a_2 - b_2|}{b_2}\right\} \tag{6}$$

where, the first part represents the influence of the size of the peak district on grey degree and the second part represents the influence of the coverage of the $L(x)$ and $R(x)$ on grey degree.

3. THE PROPOSED ALGORITHM

The Pseudo-code of the proposed algorithm was shown in figure 3.

Step 1: Input the information system S of the discretization from raw data.

Step 2: construct the decision table from the information system by applying the following steps:

Step 2.1: Establish an information matrix with given attribute value.

Step 2.2: Calculate cluster weight η_j^k (or given by experts) with the given whitenization weight function f_j^k

Step 2.3: From formula $\sigma_i^k = \sum_{j=1}^{m} f_j^k(x_{ij})\eta_j^k$ we can figure out cluster coefficient, and further determine object belonging to grey class.

Step 2.4: Construct decision table with decision attribute value regarded as the object belonging to grey class.

Step 3: Determine the levels of grey degree of grey numbers.

Step 4: for each g_c compute the g_c-lower approximation, and g_c- upper approximation of X.

Step 5: compute the reduct at different levels of grey degree of grey numbers

Step 6: compute the measure of classification quality.

Step 7: Finally extract the corresponding rule sets.

Figure 3. The Pseudo-code of the proposed Algorithm

4. CASE STUDY

To demonstrate and prove the effectiveness of the suggested algorithm, it is applied to the rotary clinker kiln (RCK) control. The rotary clinker kiln (RCK) is the main and most important part in the process of manufacturing cement. According to its capacity the capacity of the overall plant are determined. rotary clinker kiln (RCK) is a long, slightly inclined rotating cylinder as shown in figure 4, where the Calcination process of limestone occurs in the rotary clinker kiln (RCK) in temperatures over 1400°C as well as it is a highly energy-consuming process and dust and greenhouse-gas emitting during this issue. So the main goal of engineers is to increase the efficiency of the rotary clinker kiln (RCK) to decrease the CO_2 emission and achieve the environmental conditions which results in sustainable development of cements industry. It worth noting that due to technical and operational constraints it is impossible to observe what is happen inside the rotary clinker kiln (RCK) so it is necessary to find a method to give us the chance to control the rotary clinker kiln (RCK) during operation for sustainability of producing cement. This issue is the main goal of this paper where it is aim is to build a rule based control of rotary clinker kiln (RCK) for optimal control of the process and used as a decision-making support for operators and field engineers.

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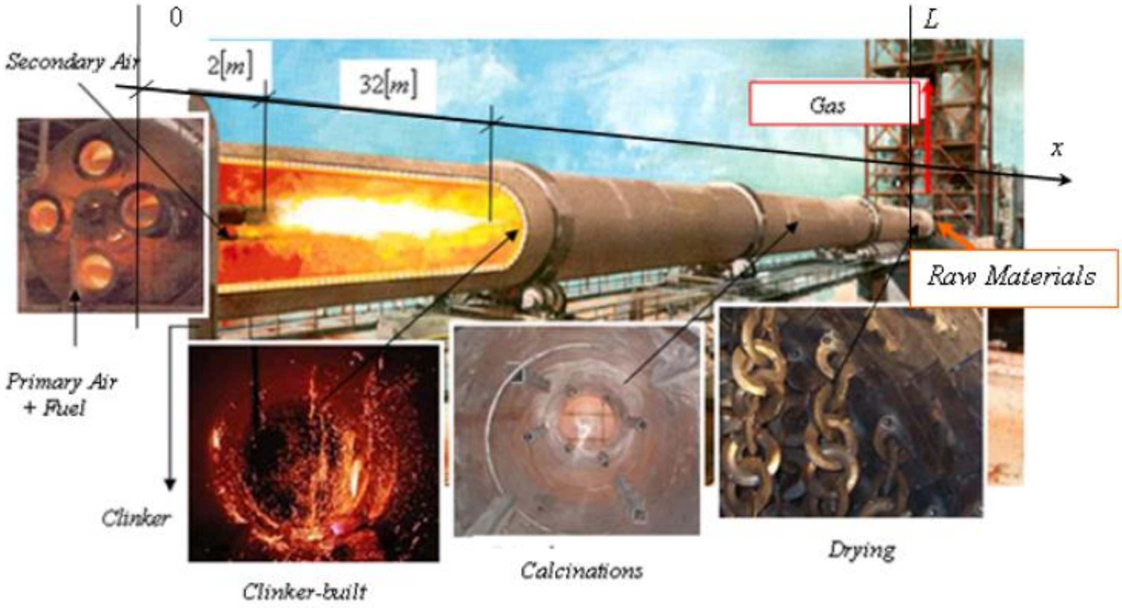

Figure 4. The rotary clinker kiln (RCK)

In order to build a rule based control of rotary clinker kiln (RCK) it is required to take into consideration the expert's behavior during the control process. Expert's knowledge naturally represented as a set of decision rules in the form: IF {set of conditions} TREN {set of decisions} to represent dependencies between conditions and corresponding decisions. In this paper a rule based control will be constructed based on Rough Sets Theory and Grey System for Sustainability of Rotary Clinker Kiln , the a rule based control system consists of all different decision rules after removing contradictory decision rules, elimination of condition attributes which do not have any influence on the decision.

Due to technical and operational constraints RCK is traditionally divided to many zones, the most important zone is the burning zone. So the main strategy for sustainability control of RCK depend on remaining the clinker with the required physical and chemical characteristics , this is done by the stoker which evaluates and classify the state of burning zone and controls the kiln. The state of burning zone is specified by four items: burning zone temperature, burning zone color, clinker granulation in burning zone and finally inside color of the kiln. While the state of a rotary clinker kiln may be one of : "very weak kiln" , "weak kiln", "kiln weakening or becoming sharp", "sharp kiln", "over sharpened kiln". Table 1 represents the details of these items and Table 2 represents the classification of RCK. For best performance it is required that the state of rotary clinker kiln always be "sharp kiln". So the control process is done by the stoker to determination of such values of the decision attributes which will bring the rotary clinker kiln to a desired state, i.e. "sharp kiln". These decision attributes are: kiln revolutions and coal consumption measured in revolutions of the coal worm and their values are represented in Table 1. Table 3 represents the decision table which describes the control of RCK. After that the proposed algorithm was applied to decision table shown in table 3 and the levels of grey degree of grey numbers are defined as follows:

- The grade of white numbers is defined as

$$g_c = 0 : \underline{\mu}_x(x) = 0 \Rightarrow \underline{g}_c = 0 \text{ and } \overline{\mu}_x(x) = 1 \Rightarrow \overline{g}_c = 0$$

- Grade 1 of grey numbers is defined as

$$g_c = 1 : \underline{\mu}_x(x) \in (0, 0.1] \Rightarrow \underline{g}_c = 1 \text{ and } \overline{\mu}_x(x) \in [0.9, 1) \Rightarrow \overline{g}_c = 1$$

- Grade 2 of grey numbers is defined as

$$g_c = 2 : \underline{\mu}_x(x) \in (0.1, 0.2] \Rightarrow \underline{g}_c = 2 \text{ and } \overline{\mu}_x(x) \in [0.8, 0.9) \Rightarrow \overline{g}_c = 2$$

- Grade 3 of grey numbers is defined as

$$g_c = 3 : \underline{\mu}_x(x) \in (0.2, 0.3] \Rightarrow \underline{g}_c = 3 \text{ and } \overline{\mu}_x(x) \in [0.7, 0.8) \Rightarrow \overline{g}_c = 3$$

- Grade 4 of grey numbers is defined as

$$g_c = 4 : \underline{\mu}_x(x) \in (0.3, 0.4] \Rightarrow \underline{g}_c = 4 \text{ and } \overline{\mu}_x(x) \in [0.6, 0.7) \Rightarrow \overline{g}_c = 4$$

- Grade 5 of grey numbers is defined as

$$g_c = 5 : \underline{\mu}_x(x) \in (0.4, 0.5] \Rightarrow \underline{g}_c = 5 \text{ and } \overline{\mu}_x(x) \in [0.5, 0.6) \Rightarrow \overline{g}_c = 5$$

- The grade of black numbers is defined as

$$g_c > 5 : \underline{\mu}_x(x) = \overline{\mu}_x(x) \quad \underline{g}_c = \overline{g}_c > 5$$

Then the gc-lower approximation, gc- upper approximation of

X with Ip in S and the measure of classification quality was computed was computed, respectively by

$$\underline{apr}_P^{g_c}(X) = \cup\left\{\frac{|I_P(x)| \cap X}{|I_P(x)|} \le \bar{g}_c\right\} \quad (7)$$

$$\overline{apr}_P^{g_c}(X) = \cup\left\{\frac{|I_P(x)| \cap X}{|I_P(x)|} > \bar{g}_c\right\} \quad (8)$$

$$\gamma_P^{g_c}(P,D) = \frac{\left|\left\{\frac{|X| \cap I_P(x)}{|I_P(x)|} \le \bar{g}_c\right\}\right|}{|U|} \quad (9)$$

The final decision tree is presented in figure 5 which represent the final set of decision rules based control of the stoker during the control process of RCK. By conducting a comparison with results obtained by [19] an excellent agreement was found.

Table 1: The coding value of the condition attributes and decision attributes

item	Parameter	values
burning zone temperature	BT	{1,2,3,4} where $1=(1380°C-1420°C)$ $2=(1421°C-1440°C)$ $3=(1441°C-1480°C)$ $4=(1481°C-1500°C)$
burning zone color	BC	{1,2,3,4,5}, where 1=scarlet, 2=dark pink, 3=bright pink, 4=decidedly bright pink, 5=rosy white
clinker granulation in burning zone	CG	{1,2,3,4}, where 1=fines, 2=fines with small lumps, 3=distinct granulation, 4=lumps
inside color of the kiln	CK	{1,2,3}, where 1=distinct dark streaks, 2=indistinct dark streaks, 3=no dark streaks
"very weak kiln"	VW	
"weak kiln"	W	
"kiln weakening or becoming sharp"	WB	
"sharp kiln"	S	
"over sharpened kiln"	OS	
kiln revolutions	KR	{1,2}, where 1= 0.9 rpm , 2 = 1.22 rpm
coal worm revolutions	CR	{1,2,3,4}, where 1= 0 rpm , 2 = 15 rpm , 3 = 20rpm , 4 = 40rpm

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Table 2: Classification of RCK

	Conditional attributes "The state of burning zone"				Decision attribute "state of a rotary clinker kiln"
	BT	BC	CG	CK	
x1	1	1	1	1	VW
x2	1	1	1	1	VW
x3	2	1	1	1	VW
x4	2	2	1	1	W
x5	2	2	1	1	W
x6	1	2	1	1	W
x7	2	2	1	1	W
x8	2	2	2	1	WB
x9	1	2	2	1	WB
x10	2	2	2	1	WB
x11	2	2	2	1	WB
x12	3	2	2	1	WB
x13	3	2	2	2	WB
x14	2	2	2	2	WB
x15	2	2	2	2	WB
x16	1	2	2	1	WB
x17	2	2	2	1	WB
x18	2	2	2	1	WB
x19	3	2	2	1	WB
x20	3	3	2	1	S
X21	3	3	2	1	S
x22	4	3	3	1	S
x23	4	3	3	1	S
x24	3	3	3	1	S
x25	2	3	3	1	S
x26	2	3	3	1	S
x27	2	3	3	1	S
x28	3	4	3	1	S
x29	4	4	3	1	S
X30	4	4	4	1	OS

Table 3: The decision table

	Conditional attributes				Decision attribute	
	BT	BC	CG	CK	KR	CR
x1	3	1	3	2	2	4
x2	3	2	3	2	2	3
x3	3	1	3	2	2	4
x4	4	2	3	2	2	2
x5	4	2	4	2	2	2
x6	4	2	4	3	2	2
x7	4	1	4	3	2	2
x8	4	1	3	3	2	2
x9	4	1	3	2	2	2
x10	4	3	3	2	2	2
x11	3	1	3	2	2	4
x12	3	1	3	2	2	4
x13	3	1	3	2	2	4
x14	3	3	3	2	2	3
x15	3	3	2	2	2	4
x16	3	1	2	2	2	4
x17	3	2	2	2	2	4
x18	3	2	3	2	2	3
x19	3	2	3	2	2	3
x20	4	2	3	2	2	2
x21	4	2	4	2	2	2
x22	4	2	4	3	2	2
x23	4	1	4	3	2	2
x24	4	1	3	3	2	2
x25	4	1	3	2	2	2
X26	4	3	3	2	2	2
X27	3	3	3	2	2	3
X28	3	3	3	2	2	3
X29	3	3	2	2	2	4
X30	3	3	2	2	2	4
X31	3	1	2	2	2	4
X32	3	2	2	2	2	4
X33	3	2	2	2	2	4
X34	3	2	3	2	2	3
X35	3	2	3	3	2	3
X36	4	2	3	3	2	2
X37	4	2	4	3	2	2
X38	4	1	4	3	2	2
X39	4	1	3	3	2	2
X40	4	1	3	2	2	2
X41	4	1	3	2	2	2
X42	4	3	3	2	2	2
X43	4	3	3	2	2	2
X44	3	3	2	2	2	4
X45	3	3	2	2	2	4
X46	3	1	3	2	2	4
X47	3	1	3	2	2	4
X48	3	1	3	2	2	4
X49	3	1	3	2	2	4
X50	3	1	3	2	2	4

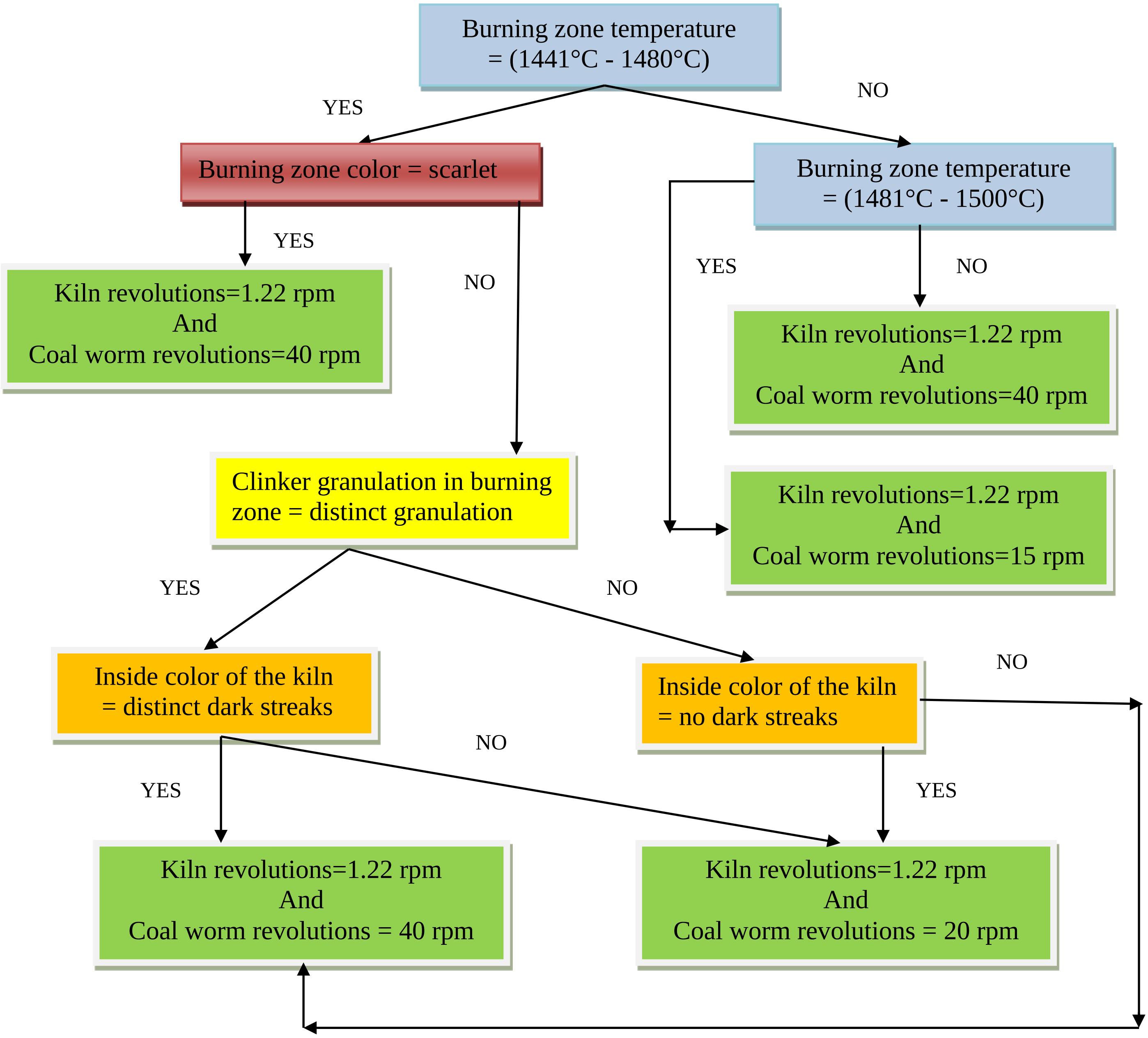

Figure 5. The final decision tree

5. CONCLUSION

In this paper a hybrid approach based on rough sets theory and grey system was presented to construct a rule based control for Sustainability of Rotary Clinker Kiln. The results show that the suggested method is both efficient for the space and time complexities, it can decrease the cost of diagnosis system; it also helps obtaining small rule sets with good performance for most mechanical machines.

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