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EMISSION CONTROL IN ROTARY KILN LIMESTONE CALCINATION USING PETRI NET MODELS

A Thesis

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To my family, friends and my mentors
for their eternal love and support

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ABBREVIATIONS

CEMS	Continuous Emission Monitoring System
DAA	Dry Absorbent Addition
DES	Discrete Event System
ECE	Electrical and Computer Engineering
FQW	Fuel Quality Waste
IUPUI	Indianan University-Purdue University Indianapolis
SNCR	Selective Non-Catalytic Reduction
US EPA	United States Environmental Protection Agency
WGS	Wet Gas Scrubber

NOMENCLATURE

CO	Carbon Monoxide
CO_2	Carbon Dioxide
SO_2	Sulfur Dioxide
O_3	Ozone
Pb	Lead

ABSTRACT

Saini, Amit K. M.S.E.C.E., Purdue University, August 2016. Emission Control in Rotary Kiln Limestone Calcination Using Petri Net Models. Major Professor: Lingxi Li.

The idea of emission control is not new. Different industries have been putting in a lot of effort to limit the harmful emissions and support the environment. Keeping our earth green and safe for upcoming generations is our responsibility. Many cement plants have been shut down in recent years on account of high emissions. Controlling SO_2, NO_x and CO emissions using the Petri net models is an effort towards the clean production of cement. Petri nets do not just give a pictorial representation of emission control, but also help in designing a controller. A controlled Petri net can be potentially implemented to control the process parameters. In Chapter 2, we discuss the Petri nets in detail. In Chapter 3, we explain the modeling of emissions using the Petri nets. A controlled emission model is given in Chapter 4. A general Petri net model is considered to design the controller, which can be easily modified depending on the specific requirements and type of kiln in consideration. The future work given at the end is the work in progress and a neural network model will likely be integrated with the Petri net model.

1. INTRODUCTION

As the effect of global warming and atmospheric pollution become more visible, the world has become more concerned about these changes. Environmental regulations across the world are getting more stringent and meeting the market demand and compliance requirements at the same time is a major challenge for many industries nowadays. The cement industry is not an exception; it has major effect of changing environmental regulation [1], [2]. The government of many countries are monitoring cement plant emissions closely and have strict regulations to limit such emissions. The United States cement industry is the world's third largest of its kind. Federal and state Environmental Protection Agencies (EPA) are regulating these emissions in the United States. The Clean Air Act was first passed in 1963 and amended later in 1970 and 1990, requires EPA to establish air quality standards to protect public health. Under the act, EPA has set standard for six common pollutant i.e. CO, O_3, Pb, NO_2, SO_2 and particulate matters, also known as criteria pollutants collectively. All the cement plants in the United States are required to submit their monthly emission report to US EPA.

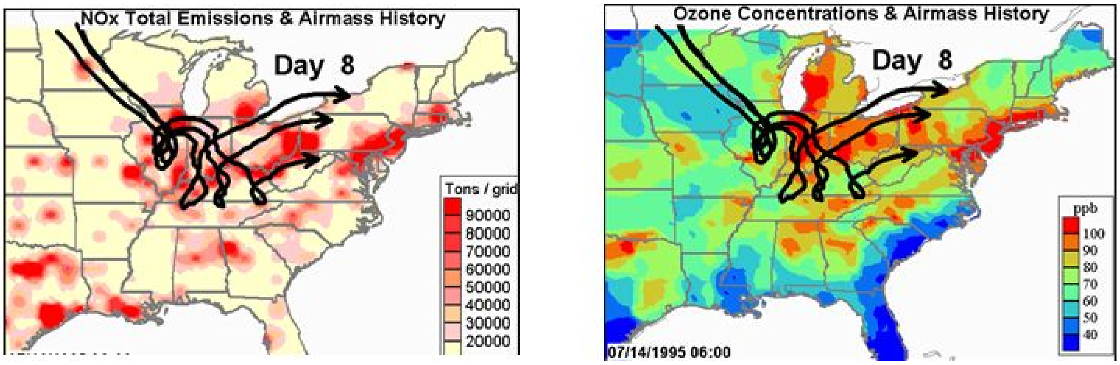

Fig. 1.1.: Effect of NO_x on Ozone: Published by US EPA in NO_x bulletin [3]

Cemex's cement plant in Davenport, California was facing similar challenges in the decade of 2000-2010 [1]. The plant was eventually shutdown in December 2010 after 105 years of successful operation. The primary reason for the shutdown was excessive expenses in order to meet the local environmental regulations. Lafarge North America ceased its clinker production at the end of 2010 on the similar ground. In a recently published sustainability report by LafargeHolcim, world's largest cement manufacturer, the company targets to reduce CO_2 emissions by 40% and SO_x and NO_x by 30% in two stages by the year 2030.

1.1 Pyroprocessing

In cement manufacturing, a mixture of limestone, iron, silica and aluminum is fed to the rotary kiln, they are collectively referred as raw meal. The complete process of transformation from raw meal feed to the exit of clinker that takes place inside the kiln is known as Pyroprocessing. Preheating of raw meal, followed by calcination of limestone, formation of oxides of carbon, sulfur, nitrogen and other gases takes places under so called pyroprocessing. Clinker, so formed, is grinded (sometimes with gypsum) to form the final product called cement. Rotatory kilns, where pyroprocessing takes place, are considered as the largest moving piece of a machinery in any industry.

1.2 Pyroprocessing emissions

Pyroprocessing is the primary source of emissions in a cement manufacturing facility [4]. When the raw meal is heated beyond 800° C many by-products are generated along with the desired clinker. The combustion of fuel and process of calcination result in the gas emission that mainly includes oxides of carbon, sulfur and nitrogen [5]. The gases, before exiting through the stack into the atmosphere, are analyzed by CEMS that includes multiple gas analyzers. The analyzer system continuously monitors the percentage of CO, CO_2, NO_x, SO_x and O_2 in the gas exiting the kiln. Many cement plants are making modification or have already made some modifications in pyroprocessing to meet the environmental regulations while keeping up with the production to meet market requirements [6], [7]. Thus, emission control becomes a critical piece in cement manufacturing and that brings the idea of using Petri net modeling to control the emissions by not letting the process to reach a state of high emission. To better design the Petri net controller, in following two sections we explain the pyroprocessing and the formation of SO_x and NO_x in the process.

1.3 Formation of oxides of Sulfur in pyroprocessing

Table 1.1 shows the reactions involving sulfur that takes place inside the kiln during the pyroprocessing. As discussed in [5], SO_2 emission to the atmosphere depends on the quality of raw meal and fuel available to a cement plant. Contained in the raw meal and the fuel, sulfur enters the process mainly in the form of sulfates, sulfides and organic sulfur compounds [5]. In the process, the sulfur compounds may either be reduced or oxidized to form gaseous SO_2. Unless absorbed in the raw meal limestone in other parts of the process, SO_2 will leave the pyroprocessing system with the exit gases. At low temperatures, SO_2 can be further oxidized to form (gaseous) SO_3. However, due to the low retention time of exhaust gases at low temperature in the cement kiln and the raw grinding system, more than 99% of the sulfur emitted via the stack will be in the form of SO_2 [5]. Therefore, in the emission from a cement kiln system it is unnecessary to control other sulfur components than SO_2.

1.4 Formation of oxides of Nitrogen in pyroprocessing

Molecular nitrogen of combustion air and kiln fuel oxidize to form nitrogen oxide, NO, during fuel combustion. Significant oxidation of the molecular nitrogen of the combustion air takes place in oxidising flames with a temperature above 1200° C (2200° F) [5]. The NO formed in this way is termed as thermal NO, as opposed to

Table 1.1: Formation of SO_x

Location	**Formation of SO_2**	**Absorption of SO_2**
Preheating Zone	Sulphides + $O_2 \longrightarrow$ Oxides + SO_2 Organic S + $O_2 \longrightarrow SO_2$	$CaCO_3 + SO_2 \longrightarrow CaSO_3 + CO_2$
Calcining Zone	Organic S + $O_2 \longrightarrow SO_2$ $CaSO_4 + C \longrightarrow CaO + SO_2 + CO$	$CaO + SO_2 \longrightarrow CaSO_3$ $CaSO_3 + \frac{1}{2}O_2 \longrightarrow CaSO_4$
Burning Zone	Fuel S + $O_2 \longrightarrow SO_2$ Sulphates $\longrightarrow$ Oxides + SO_2 + $\frac{1}{2}O_2$	$Na_2O + SO_2 + \frac{1}{2}O_2 \longrightarrow Na_2SO_4$ $K_2O + SO_2 + \frac{1}{2}O_2 \longrightarrow K_2SO_4$ $CaO + SO_2 + \frac{1}{2}O_2 \longrightarrow CaSO_4$

the NO formed by oxidation of the nitrogen compounds in the fuel which is termed as fuel NO. Since the flame temperature in the rotary kiln is always well above 1400° C (2550° F), considerable amounts of thermal NO are generated here. In the lower temperature zones of the kiln system, further oxidation of NO to NO_2, may take place. However, NO_2, normally accounts for less than 10% of the NO_x emission from a cement kiln system stack [5]. In a survey conducted by the US EPA, effect of

Table 1.2: Formation of NO_x

Location	**Formation of NO_x**
Burning zone	$N + O \longrightarrow NO$ $N + NO \longrightarrow N_2 + O$

NO_x in Ozone depletion is clearly visible [3]. Figure 1.1 shows the outcome of the survey [3]. Petri nets model provides an effective way to model and analyze timed and untimed DES. Due to pictorial representation of different states of the system it becomes easier to analyze a Petri net model. Designing a controller in a given Petri net model, based on the state based constraints, is considered as a simplified and effective way to control a discrete system.

2. PETRI NETS

2.1 Definition

Petri net provides the way of modeling a DES. These models were first published by Carl Adam Petri in 1962 as a part of his PhD thesis. Petri net includes the explicit set of conditions, known as places. A place can enable or disable an event, known as transition. This combination of places and transitions of Petri nets can easily, at least for less complex systems, be represented graphically. The resulting graph is known as a Petri nets model. A simple Petri nets model is a weighted directed bipartite graph represented as,

$$N = (P, T, A, W)$$

where,

- “P”is the finite set of places, one of the node in Petri net graph usually represented by a circle or double circle. In rest of this paper, a variable ‘n’ is used to represent the total number of places in a Petri net. Mathematically,

$$P = \{p_1, p_2, p_3 .....p_n\} \quad where, n \in \mathbb{N} \tag{2.1}$$

- “T”is the finite set of transitions, another node in Petri net graphical representation usually represented as a line or a rectangle. From here onward, the variable ‘m’ is used to represent the total number of transitions in a Petri net. Mathematically,

$$T = \{t_1, t_2, t_3 .....t_m\} \quad where, m \in \mathbb{N} \tag{2.2}$$

- “A”is the set of arcs connecting various non-similar nodes in a graph, that is, an arc in a Petri net model may connect a place to a transition or vice versa.

Arcs never connect a place to another place or a transition to another transition. This is based on the fact that the condition of a system cannot magically change without any occurrence of an internal or external event. Arcs could be an input or output arc represented by an arrow pointing towards the direction of flow of tokens, discussed later individually. Mathematically,

$$A \subset (P \times T) \cup (T \times P)$$

- “W”as a set of natural numbers represents the weight associated with each arc in a Petri net model. The idea of weight is to use a number instead of using multiple connecting arcs. An arc without a mentioned weight is assumed to have unity weight. A natural number on top or bottom of the arc represents its weight, unless Petri net is continuous where the weight can be any positive real number. An absence of the arc between two nodes indicates that there is no direct relation between that particular condition and event. In Petri net dynamics an absence of arc is assumed to have zero weight for the purpose of mathematical calculations. Mathematically, the weight is a function of arc defined as,

  $$w : A \longrightarrow \{1, 2, 3.....\} \tag{2.3}$$

- $A \subset (P \times T)$ is known as the set of input arcs to the transitions in a Petri net graph. These arcs point from the places to the transitions and such places are known as input to the transitions. $I(t_j)$ is commonly used to represent the set of input places to a particular transition t_j. Thus,

  $$I(t_j) = \{p_i \in P \ \mid \ (p_i, t_j) \in A\}$$

  Similarly, $I(p_i)$ represents the set of input transitions to a place p_i which can be defined as,

  $$I(p_i) = \{t_j \in T \ \mid \ (t_j, p_i) \in A\}$$

- $A \subset (T \times P)$ is the set of output arcs of the transitions in a Petri net graph. These arcs point from the transitions to the places and such places are known as output places to the transitions. $O(t_j)$ is commonly used to represent the set of output places to a particular transition t_j. Thus,

  $$O(t_j) = \{p_i \in P \ \mid \ (t_j, p_i) \in A\}$$

  Similarly, $O(p_i)$ represents the set of output transitions to a place p_i which can be defined as,

  $$O(p_i) = \{t_j \in T \ \mid \ (p_i, t_j) \in A\}$$

Note that the arcs associated to the set $I(t_j)$ are same as that associated with $O(P_i)$ although these sets are not equivalent. Figure 2.1 is a simple Petri net model that illustrates the above definitions and provides a better understanding of how different sets are determined with reference to a graph.

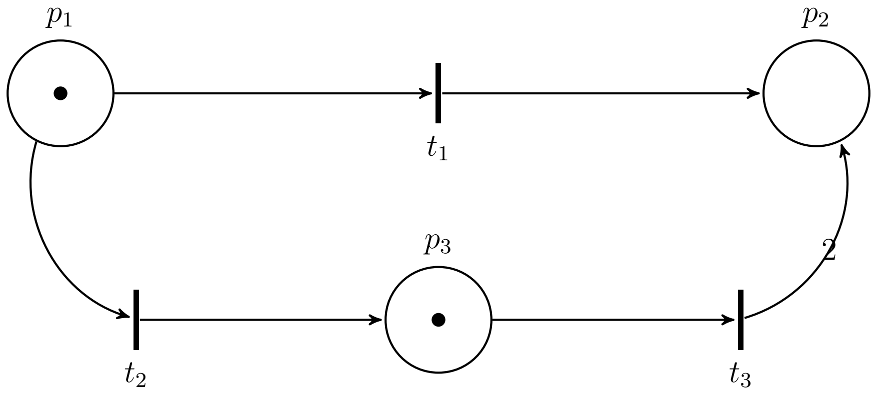

Fig. 2.1.: Simple Petri net model

As per the definition of Petri net Figure 2.1 has the following components,

$P = \{p_1, p_2, p_3\}$

$T = \{t_1, t_2, t_3\}$

$A = \{(p_1, t_1), (p_1, t_2), (t_1, p_2), (t_2, p_3), (p_3, t_3), (t_3, p_2)\}$

$W(p_1, t_1) = 1;$ $W(p_1, t_2) = 1;$ $W(p_3, t_3) = 1$

$W(t_1, p_2) = 1;$ $W(t_2, p_3) = 1;$ $W(t_3, p_2) = 2$

$I(t_1) = \{p_1\};$ $I(t_2) = \{p_1\};$ $I(t_3) = \{p_3\}$

$I(p_1) = \phi;$ $I(p_2) = \{t_1,\, t_3\};$ $I(p_3) = \{t_2\}$

$O(t_1) = \{p_2\};$ $O(t_2) = \{p_3\};$ $\mathrm{O}(t_3) = \{p_2\}$

$O(p_1) = \{t_1, t_2\};$ $O(p_2) = \phi;$ $O(p_3) = \{t_3\}$

The dots inside the places p_1 and p_2 represent the current number of tokens in the places p_1 and p_2. The set of tokens for a given Petri net is known as its marking, and will be discussed in next section. Tokens for a given model collectively represents overall state of the system.

2.2 Marking of a Petri net model

Marking is a way of defining tokens assigned to a Petri net place. Each place in a Petri net graph can have some tokens. Thus, marking M becomes a function of place as, $M : P \rightarrow I^+ = \{0, 1, 2, 3, 4, , ...\}$. A model in which all possible states are marked is known as marked Petri net. Marking adds a new dimension to the Petri net definition making marked Petri net a five-tuple (P, T, A, W, M). A Petri net can have as many markings as the number of states the system can reach. Mathematically, marking for a Petri net graph is represented as a row vector $x = [x(p_1),\, x(p_2),\, ...x(p_n)]$, here n is the total number of places in the Petri net.

Therefore the number of elements in the marking vector are equal to the number of places in the Petri net. For example, in Figure 2.1 the initial marking of the system m_0 is $[1 \;\; 0 \;\; 1]^T$.

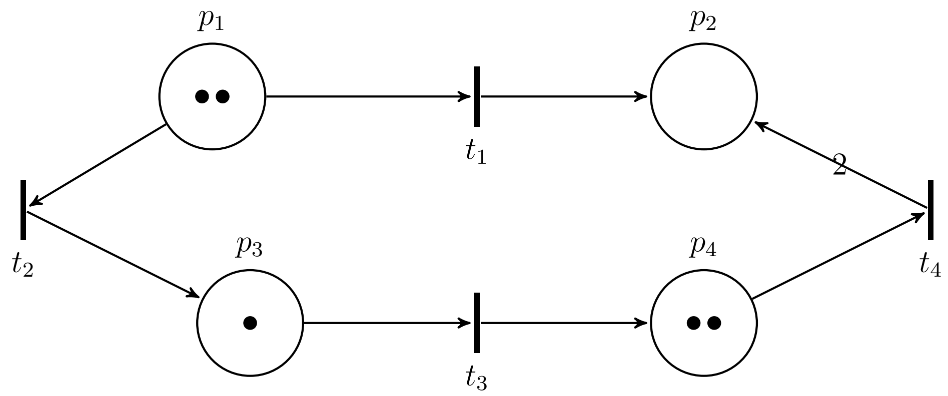

Fig. 2.2.: Petri net model with markings

2.3 State equation and transition function

With reference to Figure 2.2 transition t_2 has one input place p_1 and one output place p_3. The weight of both input and output arcs of transition t_2 is one. In Petri net models input weight of a transition determines the number of tokens needed in the associated input place to enable that transition. Thus, in Figure 2.2 transition t_2 requires at least one token in place p_1 to get enabled. In a complex Petri net there can be more than one input places to a transition and all the input places are required to have tokens at least more than or equal to the weight of the respective input arc. Mathematically, for a given transition to be enabled,

$$m(p_i) \geq W(p_i, t_j) \quad \forall p_i \in I(t_j) \tag{2.4}$$

All the transitions in a Petri net graph that satisfies the Equation 2.4 are called enabled transitions. All the transitions are enabled in Figure 2.2, while only t_1, t_2 and t_4 are enabled in Figure 2.3.

Consider an example to demonstrate Petri net dynamics. In Figure 2.2, transition t_1 has one input place p_1. Since $m(p_1) = 2 > w(p_1, t_1) = 1$, transition t_1 satisfies the Equation 2.4 and it is enabled to fire. Similarly transition t_4 is also enabled.

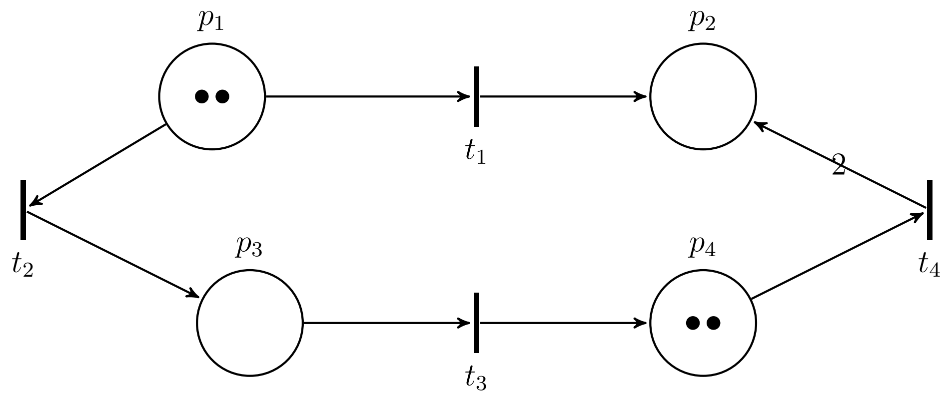

Fig. 2.3.: Marked Petri Net

An enabled transition represents a particular condition under which an event is satisfied and the system can change its state as a result of firing of a transition. Firing of a transition is equivalent to occurrence of an event in the real world. With reference to a Petri net model, when a transition fires it takes tokens from the input place that are equal to the weight of the input arc and place as many token as the weight of the output arc to the output place. For example, if transition t_4 fires in Figure. 2.3, it will move one token out of place p_4 to place two tokens in place p_2.

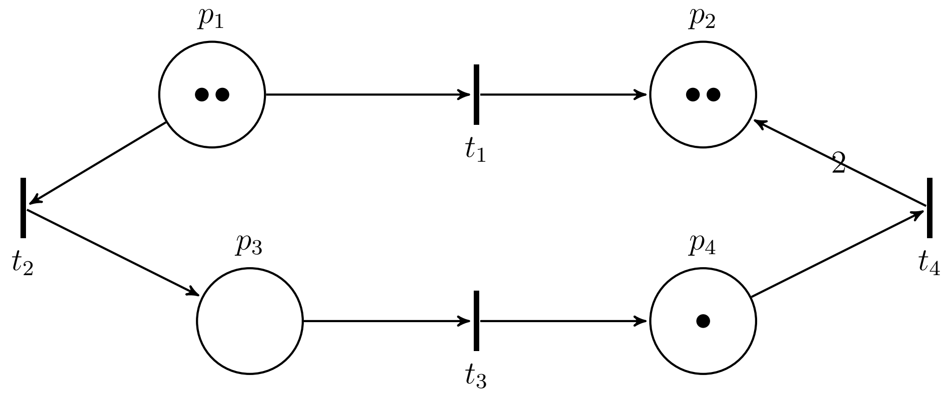

Fig. 2.4.: After t_4 fires in Figure 2.3

As t_4 fires the state of the system moves from state $[2\ 0\ 0\ 2]^T$ to $[2\ 2\ 0\ 1]^T$. Thus, by controlling the firing sequence of the transition, we can control state of the system. The sum of the number of tokens in a Petri net model may not be conserved. Total number of tokens may increase or decrease in number depending on the difference in weights of input and output arc of the firing transistion. This brings the concept of Petri net dynamics and transition equation. The transition equation for an enabled transition t_j in the system is defined as,

$$m^{'}(p_i) = m(p_i) + w(t_j, p_i) - w(p_i, t_j) \qquad \forall\, i \in (1,\ n)\ and\ j \in (1,\ m) \tag{2.5}$$

The above equation is only valid when the transition t_j is enabled, which means $m(p_i) \geq w(p_i, t_j)$. Equation 2.5 when expanded to all the places in a Petri net model, results into the "State Equation". The state equation can be understood better by using an incident matrix. Incident matrix simplifies the state transition equation. An incident matrix of a given Petri net graph is a $n \times m$ matrix defined as,

$$B = B^{+} - B^{-} \tag{2.6}$$

where B^{+} and B^{-} stand for output and input incident matrix respectively. Output incident matrix is defined as,

$$(B^{+})_{i,j} = w(t_j, p_i) \tag{2.7}$$

whereas B^{-} is defined as,

$$(B^{-})_{i,j} = w(p_i, t_j) \tag{2.8}$$

Applying Equations 2.7 and 2.8 to the Petri net model in Figure 2.3 we obtain,

$$B^{+} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$B^{-} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Using the above two matrices and Equation 2.6 we get the incident matrix,

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} - \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} -1 & -1 & 0 & 0 \\ 1 & 0 & 0 & 2 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & -1 \end{bmatrix} \tag{2.9}$$

Incident matrix gives an advantage to generalize Equation 2.5 for all the states in a given Petri net model and the resulting equation is known as State Equation. Petri net's new marking or state M_{k+1} is calculated from its current state M_k, transition firing vector X_k and incident matrix B as,

$$M_{k+1} = M_k + B \times X_k \tag{2.10}$$

where X_k for the current state k is a column vector defined as,

$$(X_k)_j = \begin{cases} 1 \quad for \quad j = firing\ transition \\ 0 \quad for \quad j = all\ other\ transitions \end{cases} \tag{2.11}$$

With the application of Equation 2.10 it can be easily calculated that how the Petri net model in the Figure 2.3 transit to Figure 2.4,

$$M_1 \quad = M_0 + B \times \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 2 \\ 0 \\ 0 \\ 2 \end{bmatrix} + \begin{bmatrix} -1 & -1 & 0 & 0 \\ 1 & 0 & 0 & 2 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & -1 \end{bmatrix} \times \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 2 \\ 2 \\ 0 \\ 1 \end{bmatrix}$$

3. KILN EMISSION PETRI NET MODELING

3.1 Understanding of kiln's emission dynamics

Rotary kiln pyroprocessing is a complex chemical process[7]. There are multiple factors that affect the kiln profile directly or indirectly. Maintaining kiln stability, burning zone and chain exit temperature along with keeping clinker quality and stack emissions under control need years of experience and every minute attention on critical kiln parameters. For the purpose of emission control, only emission profile of the kiln is modeled in this section.

Mathematical model of kiln emission is multidimensional and nonlinear in nature. The Petri net model is a pictorial representation of kiln's various states with respect to emission and how kiln emission is linked to other parameters. It helps understanding the kiln dynamics in an easier and better way compared to mathematical modeling. Following factors play major role in determining kiln emissions,

Kiln Feed → Raw meal fed to the kiln contains limestone grinded with iron, silica, clay and fly-ash. It could be either wet or dry. The feed contains some amount of sulfur that depends on limestone blasting location and other additives. This sulfur could range from 0.1% to more than 1% of the total kiln feed. Because the quantity of raw kiln feed is significantly higher than any other feed to the kiln, it becomes a major source of sulfur emission. Kiln sulfur emission has a direct relation to the sulfur content and quantity of the kiln feed.

Kiln Fuel → Kiln fuel is a site specific entity. Fuel used to burn the kiln depends on the plant's location and ease of fuel availability. Coal/coke and natural gas are obvious choices and they are comparatively cleaner, but they are not the cheapest fuel available in the market. Considering the kiln size and the amount of fuel needed to achieve the necessary temperature, small difference in fuel cost can results in significant difference in clinker production cost. Thus cement plants prefer to use fuel quality waste (FQW), hazardous and non-hazardous industrial waste, rubber tire etc as an alternative to traditional fuel. FQW is the second major contributor of kiln sulfur emissions.

Kiln Speed → Usually measured in RPH, kiln speed has direct relation to the amount of kiln feed. Speed determines how fast the material is flowing through the kiln.

ID Fan → Induced draft fan (ID Fan) provides the required air flow and hence O_2 inside the kiln required to burn the kiln fuel. It also provides a strong draft through the kiln system which helps the in proper air filter functioning.

Additives → In recent years cement plants have started using additives to reduce SO_2 and NO_x emission. DAA and WGS help reducing SO_2 emissions and SNCR helps reducing NO_x.

3.2 Emission trends and their analysis

Trends help developing a better understanding of kiln emissions and help in determining a possible relation between multiple factors affecting kiln emissions. The following are 30 days trends obtained from a cement plant in Ohio to understand the kiln emissions, which later helps in designing its Petri net models. These emissions are measured on ABB's continuous gas analyzing system, also known as CEMS. Although analyzers display a real time value of the trends, all the trends below are plotted on a 2 minutes sample time. Figure 3.1 is the trend of SO_2 emissions. It is mostly under 400 PPM with some spikes going beyond 600 PPM. Figure 3.2 shows NO_x emissions trending mostly between 100 and 500 PPM. Clearly there is no direct relation between SO_2 and NO_x emissions. Another fact supporting this trend is presence of sulfur in kiln feed and fuel whereas NO_x is generated mainly from N_2 present in atmospheric air.

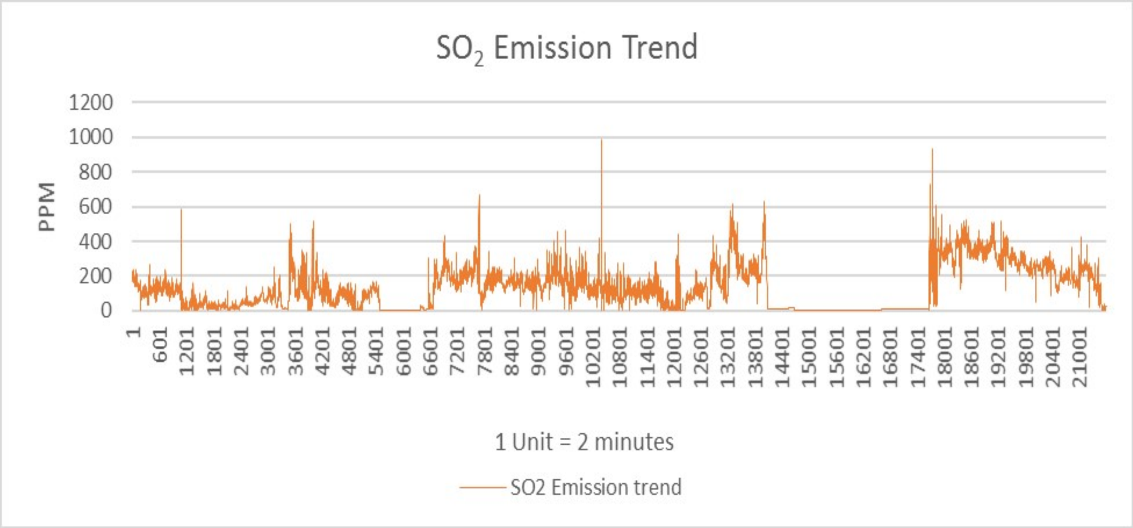

Fig. 3.1.: SO_x trend for 30 days

Third emission discussed in the next section is CO which was trending as given in Figure 3.3. Presence of O_2 (air draft) and kiln temperature are critical in reducing CO emissions. Trend of O_2, plotted after CO, when compared with CO trends justifies the theory of CO emissions. Fuel trends, FQW and natural gas, for the same period of time as the rest of the trends give further insight of chemistry going inside the kiln. Whenever kiln goes down for any reason it is first preheated using natural gas and after reaching the required temperature profile FQW is turned ON to the kiln. Plants target for 100% FQW with all the emissions under control. For cost saving

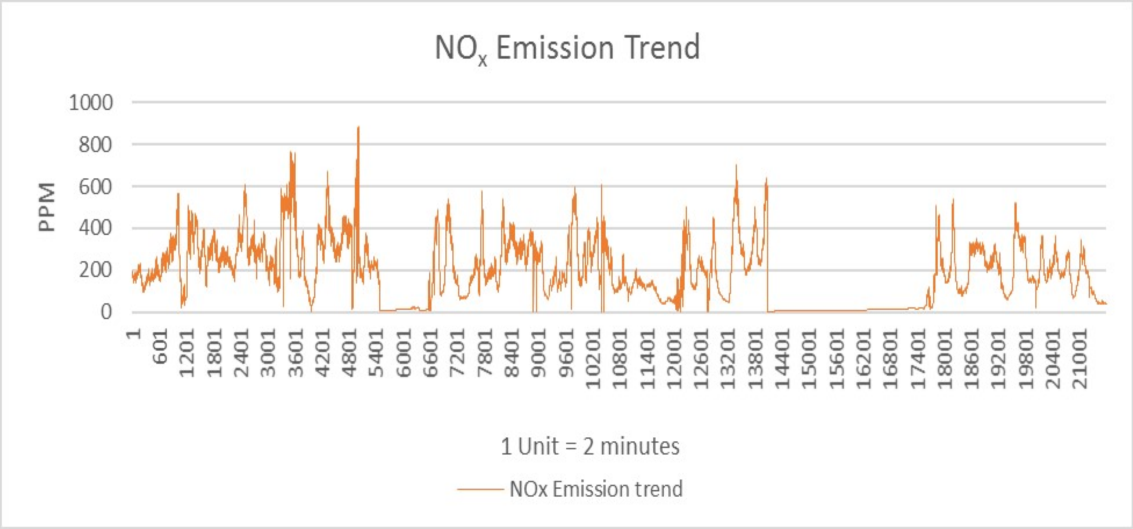

Fig. 3.2.: NO_x trend for 30 days

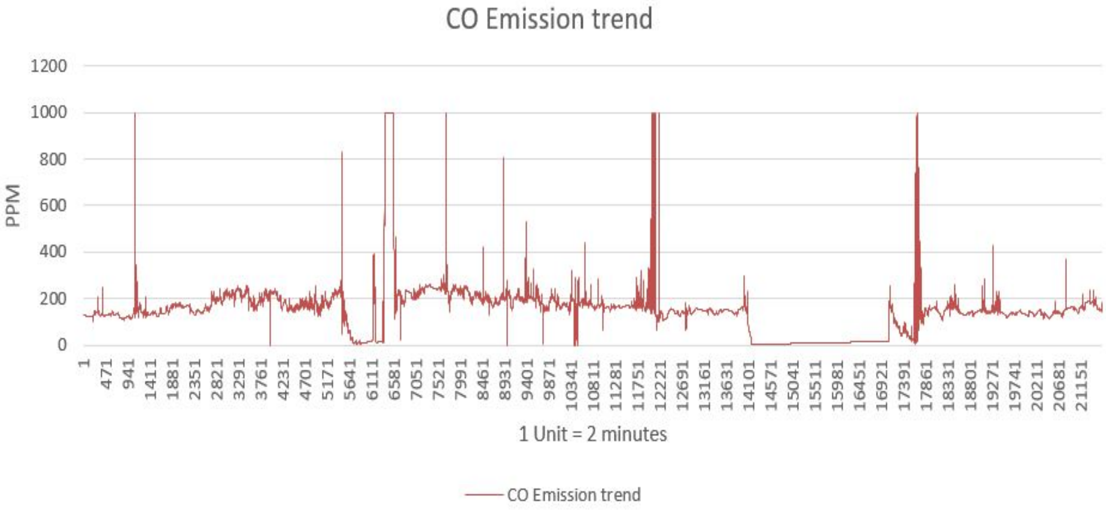

Fig. 3.3.: CO trend for 30 days

purpose, use of natural gas is avoided as long as emissions are under control. This fact is considered in Petri net modeling also. As mentioned in Section 3.1 that kiln speed determines how fast the material is flowing through the kiln. There is a linear relation between kiln speed and raw material feed. In the Figure 3.7 kiln RPH is multiplied by a factor of 8.3 and their relation is evident in the trend. This relation

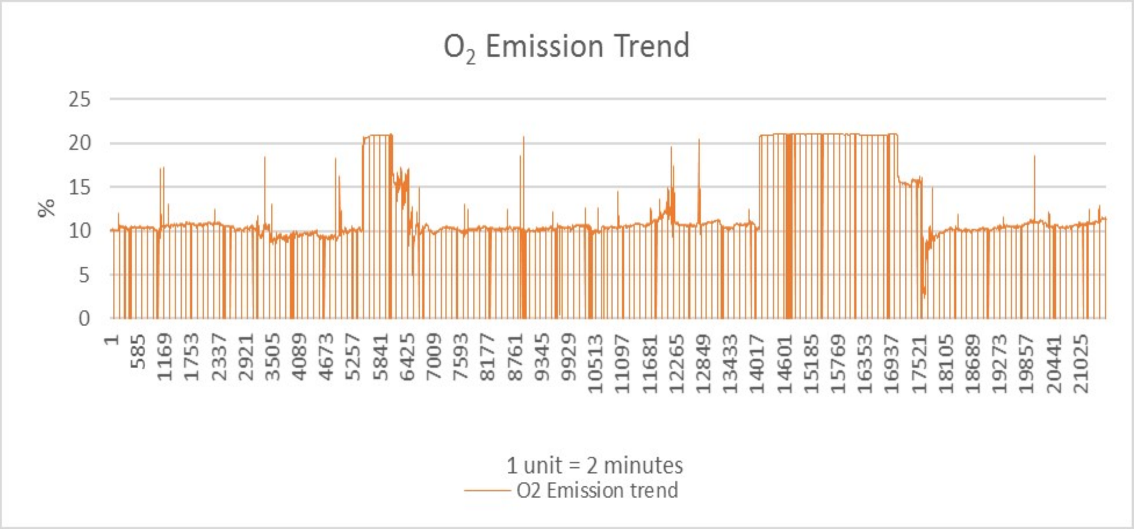

Fig. 3.4.: O_2 trend for 30 days

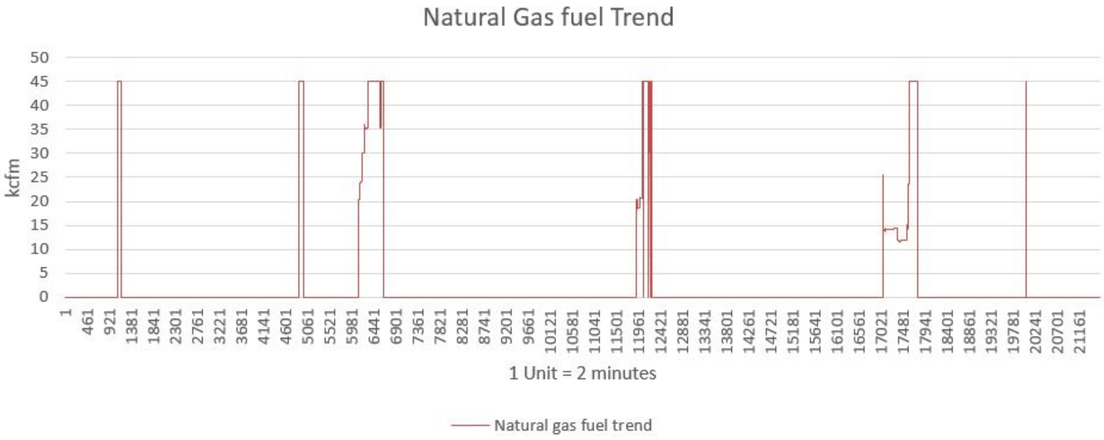

Fig. 3.5.: Natural gas fuel trend for 30 days

is commonly referred as feed speed ratio. Following relation is true for the cement plant who agreed to share its emission data,

$$Kiln\ Feed\ (l/min) = 8.3 * (Kiln\ RPH) \tag{3.1}$$

Each kiln is different and so does their kiln speed ratio. Equation 3.1 is used to calculate the number of tokens and their flow in the feed and speed states of the Petri net model discussed in the next section.

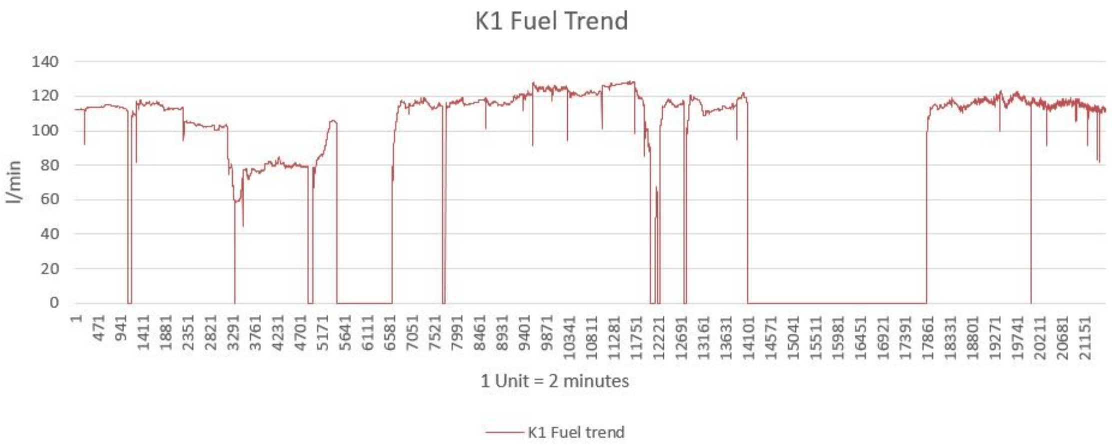

Fig. 3.6.: Kiln fuel trend for 30 days

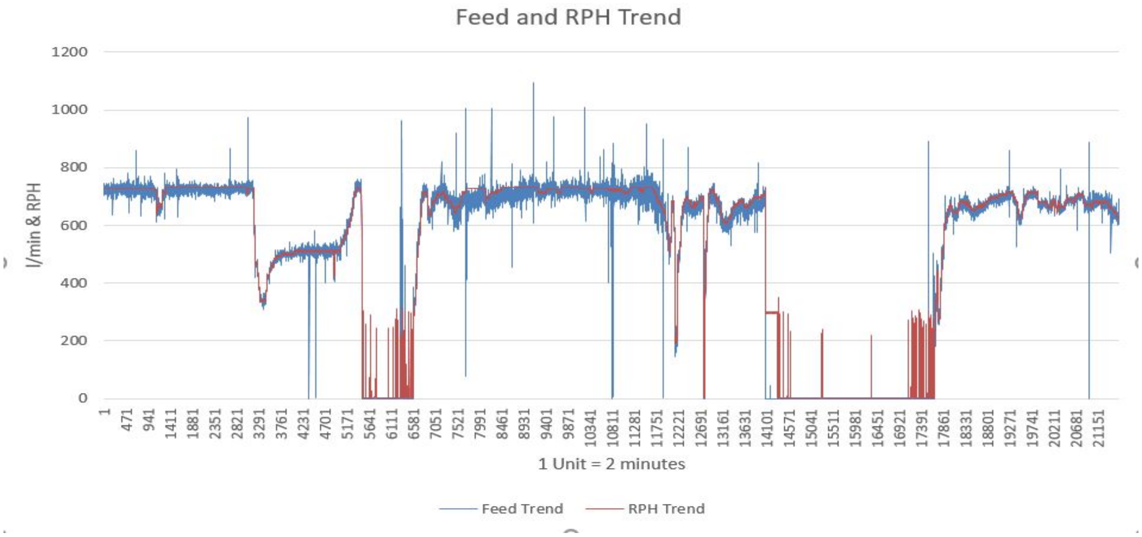

Fig. 3.7.: Slurry feed and kiln revolution combined trend for 30 days

3.3 Petri net model of SO_2 emission

After talking to multiple kiln operators and experts at different cement plants in the United States, carefully observing the trends over a very long period of time and studying the mathematical relations between different kiln controlling parameters a Petri net model is developed. The Petri net model in the Figure 3.8 captures the major states of a running kiln. This is a general SO_2 emission model which does not include any specific type of kiln as discussed in [6]. This model can easily be modified to accommodate changes in control strategy due to the variety of kiln. Additives control and temperature control also can be added to the next model. For now the focus is on emission control, leaving space for further additions in future.

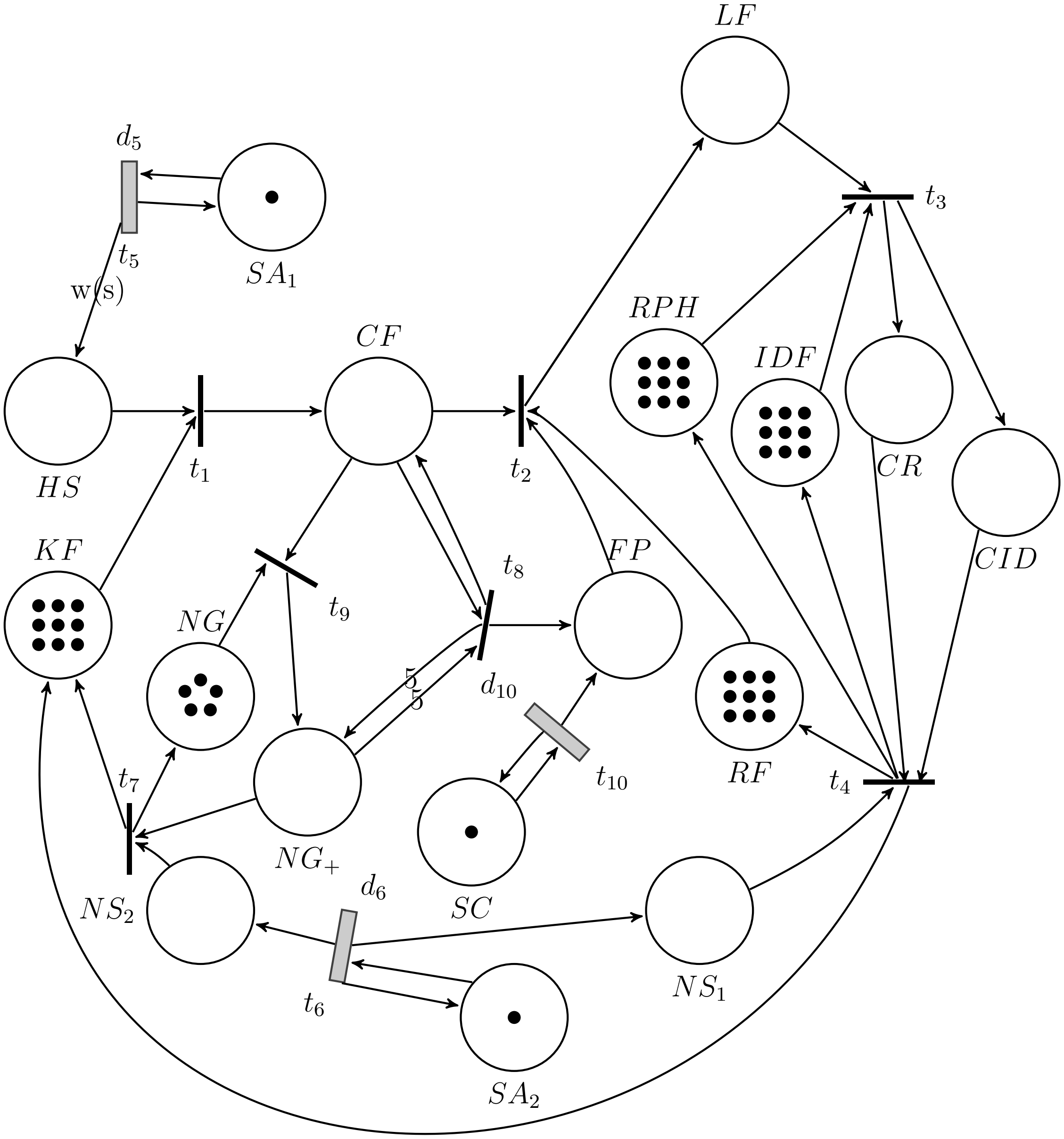

Fig. 3.8.: Kiln SO_2 Petri Net Model

The Petri net model in the Figure 3.8 has 17 places and 10 transitions. Tokens in each place has an associated multiplication factor to represent a value close to the real world measurements. All the places and their associated tokens in the Figure 3.8 are described as follows,

- **w(s):** The weight of transition t_5's output arc connecting t_5 to HS, a function of sulfur reading at the analyzer, is defined as,

  $$w(s) = \begin{cases} 1 & for \quad s = high\ sulfur\ at\ analyzer \\ 2 & for \quad s = very\ high\ sulfur\ at\ analyzer \\ 9 & for \quad s = beyond\ EPA\ permissible\ limit \end{cases} \tag{3.2}$$

  Based on Equation 3.2 t_5 will place either 1, 2 or 9 tokens to HS. This will decide further states of the kiln. High, very high and permissible limit of sulfur at analyzer is determined by the EPA regulations. Location of the plant, type of fuel used and type of kiln are some actors that establishes EPA limit on emissions.

- **SA₁ - Sulfur at Analyzer (P_1):** Sulfur going out to the open air is measured at the stack. This is real time monitoring of sulfur. Single token at this place does not represent the reading at the analyzer rather it simply shows that SO_2 analyzer is online. Since analyzers monitor the emission 24×7 there is always a token in this place. Transition t_5, when fires, will take and place one token here maintaining 1 token at this place all the time. t_5 will fire only when sulfur starts creeping up and goes beyond the threshold which indicates high sulfur content in the emission. Thus the firing of t_5 is timed. Time of fire d_5 depends on the conditions inside the kiln. If analyzer continuously reads higher sulfur it will fire transition t_5 in every 5 minutes while $w(s)$ takes a value based of sulfur reading.

  $$d_5(s) = \begin{cases} 5 & for \quad s = high\ sulfur\ at\ analyzer \\ 5 & for \quad s = very\ high\ sulfur\ at\ analyzer \\ 0 & for \quad s = beyond\ EPA\ permissible\ limit \\ \infty & for \quad s = normal\ emission\ reading\ at\ analyzer \end{cases} \tag{3.3}$$

- **HS - High Sulfur (P_2):** A token in this place is a representative of high sulfur kiln state. Only t_5 can place tokens to this place. One token in this place represents that kiln sulfur emission is high whereas two tokens in this place tells that kiln sulfur emission is critically high, and a major change is needed in kiln profile to bring the sulfur back under control. If an effective measure is not taken soon enough, the sulfur reading at analyzer can go beyond the EPA permissible limit making weight of arc, $w(s) = 9$, and kiln will reach the fuel shut down state.

- **SC - Sulfur Content (P_3):** SC represents the sulfur content in the raw feed to the kiln. Since raw feed always contains some amount of sulfur this place always has a token. Similar to transition t_5, t_{10} will fire whenever sulfur in the slurry is higher than expected. This will place one token at the place FP. Again t_{10} is a timed transition and it fires at times when raw meal sulfur percentage is above upper thresh-hold which depends on the quality of raw feed. Some plants take periodic samples and evaluate raw meal quality at the lab while some have online raw feed analyzer that continuously monitors the sulfur content in the kiln feed. $O(P_3) = t_{10}$ is a timed transition. Time function d_{10} is defined as,

$$d_{10} = \begin{cases} 5 & when\ high\ sulfur\ feed\ is\ sampled\ at\ lab \\ \infty & otherwise \end{cases} \tag{3.4}$$

- **KF - Kiln Fuel (P_4):** Number of tokens in KF represent the amount of FQW going to the kiln. Each token is equivalent to 12 liters/minute. Hence 9 tokens at this place represents 108 liters/minute fuel rate which is maximum rate for the kiln considered in this Petri net example.

- **CF - Cut Fuel (P_5):** A token in this place represents a state of the kiln when FQW rate is less than its maximum capacity of 108 liters/minute. Value of token in this place is same as in the KF place. For example, 2 tokens at this place represents that kiln FQW rate is cut down by $2 \times 12 = 24$ liters/minute. Also, 2 tokens at this place will leave 7 tokens at the KF place representing current feed rate as 84 liters/minute.

- **RF - Raw Feed (P_6):** Tokens in RF are current raw feed to the kiln. A token in RF is equivalent to 80 liters/minute. This place can take at most 9 tokens representing a maximum kiln feed capacity of 720 liters/minute. Raw feed to the kiln is continuously monitored on a flow meter. Under the normal emission state, the kiln is expected to run at full capacity hence there will be 9 tokens at this place when SO_2 emission is under control.

- **LF - Lower Feed (P_7):** A token in this place represents a lower feed state of the kiln. Tokens here will have the same value as in RF state. Therefore a token in this place shows that kiln feed is cut by 80 liters/minute.

- **FP - Feed Permissible (P_8):** A token in FP is the permission to cut the kiln feed under certain circumstances. FP place gets its tokens from the SC place as a result of firing of t_{10}. As discussed earlier, SC represents the sulfur content in the raw feed and it always has a token in place therefore transition t_{10} is always enabled. But just like t_5, transition t_{10} is going to fire only when the sulfur content in the raw meal is higher than the upper thresh-hold. Hence FP represents a state that sulfur content in the raw meal is higher than expected and it will allow to cut the feed to the kiln if sulfur reading at analyzer goes up at the same time. If FP has no tokens and CF has a token, the only action possible is to fire transition t_9 and add natural gas to the kiln. After the state NG_+ gets all 5 tokens from NG, transition t_8 gets enabled. t_8 then fires allowing to cut the feed to the kiln. The reasoning behind this logic is that when no more natural gas is available and kiln is still at high sulfur state then cutting feed the only second option left.

- **RPH - Current Revolution (P_9):** This place represents the current speed of the kiln in revolution per hour (RPH). Kiln RPH has a direct relation with the kiln feed hence whenever LF has a token t_3 is going to take a token from RPH taking kiln to a lower RPH state. Each token in RPH is equivalent to 9.6 RPH.

- **CR - Cut Revolution (P_{10}):** After firing, t_3 takes a token from RPH and places it in CR representing that kiln speed is cut down.

- **IDF - Induced Draft Fan (P_{11}):** Tokens in IDF represent the current state of the ID fan in terms of percentage. 9 tokens in Figure 3.8 are representing 99% speed of the ID fan. Hence, one token is equivalent to 11%.

- **CID - Cut Induced Draft (P_{12}):** Kiln ID fans speed is reduced by 11% whenever there is token in the place CID

- **$\mathbf{NS_1}$ and $\mathbf{NS_2}$** - Normal Sulfur (P_{13} and P_{14}): Both states NS_1 and NS_2 represent that kiln is running well under the permissible sulfur limit. Both the places get tokens simultaneously when transition t_6 fires. Transition t_6 is always enabled and it fires only when reading at CEMS drops down from a high sulfur to a normal sulfur emission. t_6 will not fire if the kiln is constantly running under normal sulfur emission.

- **NG - Natural Gas (P_{15}):** Each token in this place is equivalent to 9 kcfm unit of natural gas. 5 token in this place represents that kiln has 45 kcfm natural gas available. This is just the availability of natural gas to the kiln.

- **$\mathbf{NG_+}$:** - Natural Gas ON (P_{16}): A token travels from NG to NG_+ when t_9 fires under cut fuel condition. This state represents that natural gas is turned on to the kiln. Tokens have same value as in the place NG.

- **$\mathbf{SA_2}$** - Sulfur at Analyzer(P_{17}): This place represents that analyzer is online and sulfur going out through the stack to the open air is measured at the analyzer.

Further analysis reveals that the Petri net model in the Figure 3.8 has tokens conserved for different process parameters. It can also be observed by analyzing the model's reachability tree. Below are few examples of conserved tokens,

$$M_{NG} + M_{NG_+} = 5 \tag{3.5}$$

$$M_{RPH} + M_{CR} = M_{IDF} + M_{CID} = 9 \tag{3.6}$$

Due to the conservation of tokens these process variables will never go beyond the permissible limit and model will always represent a real world situation.

3.4 Petri net model of NO_x emission

Figure 3.9 is timed Petri net model of kiln NO_x emission based on the general functionality of the kiln. All the states in NO_x emission Petri net model are same as described for the SO_2 Petri net model with some exceptions discussed on next page.

- **$\mathbf{NA_1}$ and $\mathbf{NA_2}$- Nitrogen at Analyzer:** Nitrogen leaving the stack out to the open air is measured at the stack CEMS. Transition t_5 and t_6 when fires, will take and place one token to this place. t_5 will only fire when the nitrogen reading goes beyond the threshold. The time of fire d_5 depends on the conditions inside the kiln. If analyzer continuously reads higher nitrogen transition t_5 will fire in every 5 minutes while $w(n)$ takes a value based on nitrogen reading. Both $w(n)$ and d_5 are function of nitrogen reading at analyzer defined as,

$$w(n) = \begin{cases} 1 & for \quad n = high\ sulfur\ at\ analyzer \\ 2 & for \quad n = very\ high\ sulfur\ at\ analyzer \\ 9 & for \quad n = beyond\ EPA\ permissible\ limit \end{cases} \tag{3.7}$$

$$d_5(n) = \begin{cases} 5 & for \quad n = high\ sulfur\ at\ analyzer \\ 5 & for \quad n = very\ high\ sulfur\ at\ analyzer \\ 0 & for \quad n = beyond\ EPA\ permissible\ limit \\ \infty & for \quad s = normal\ emission\ reading\ at\ analyzer \end{cases} \tag{3.8}$$

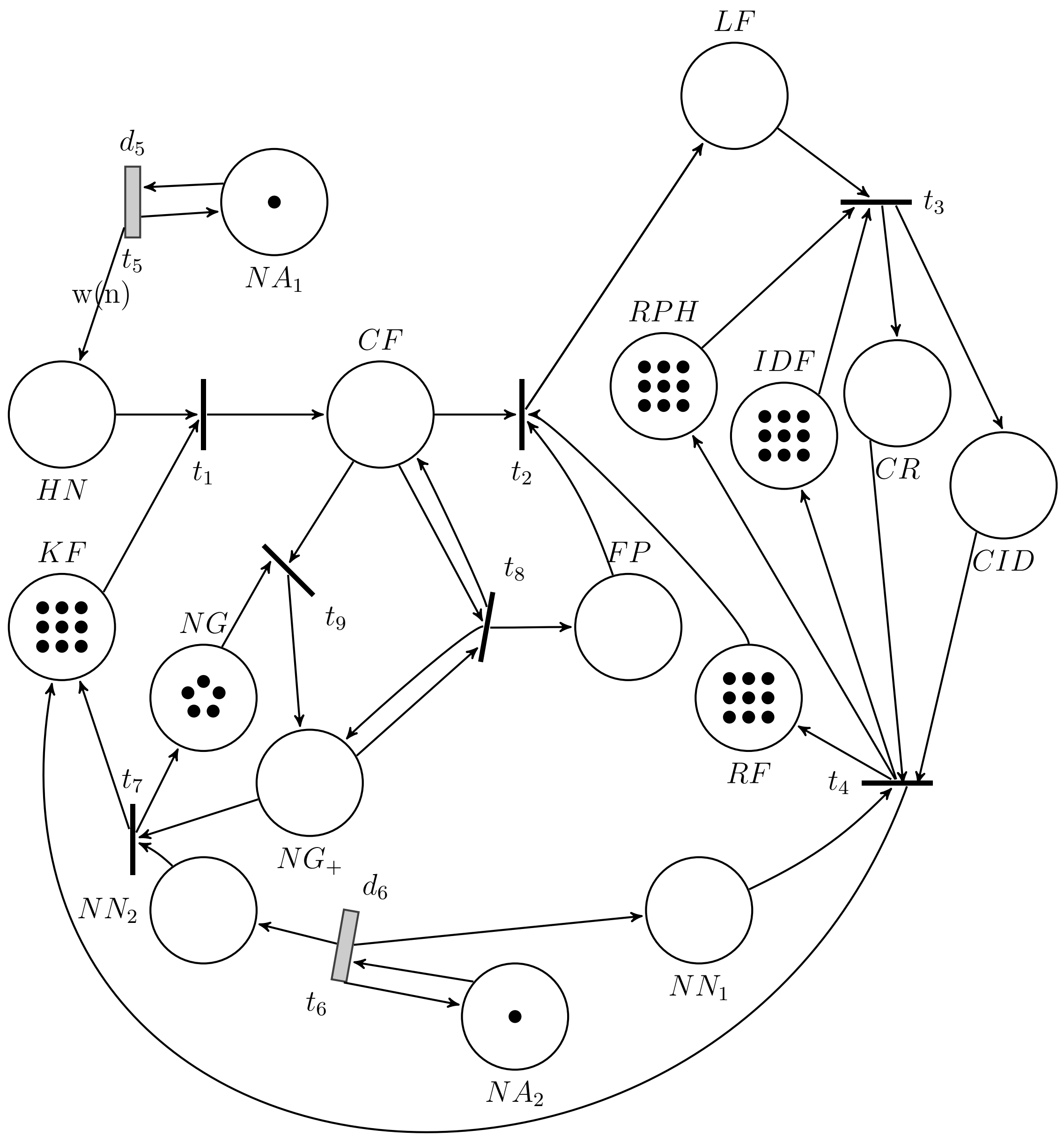

Fig. 3.9.: Kiln NO_x Petri Net Model

- **HN - High Nitrogen:** A token in HN represents high nitrogen in the kiln.
- **NN_1 and NN_2 - Normal Nitrogen at Analyzer:** A token in both of these places represents that kiln is back into normal nitrogen emission state from a high nitrogen state.

3.5 Petri net model of CO emission

Figure 3.10 represents the modeling of CO emission using Petri net. A brief description of different states in the model are described below,

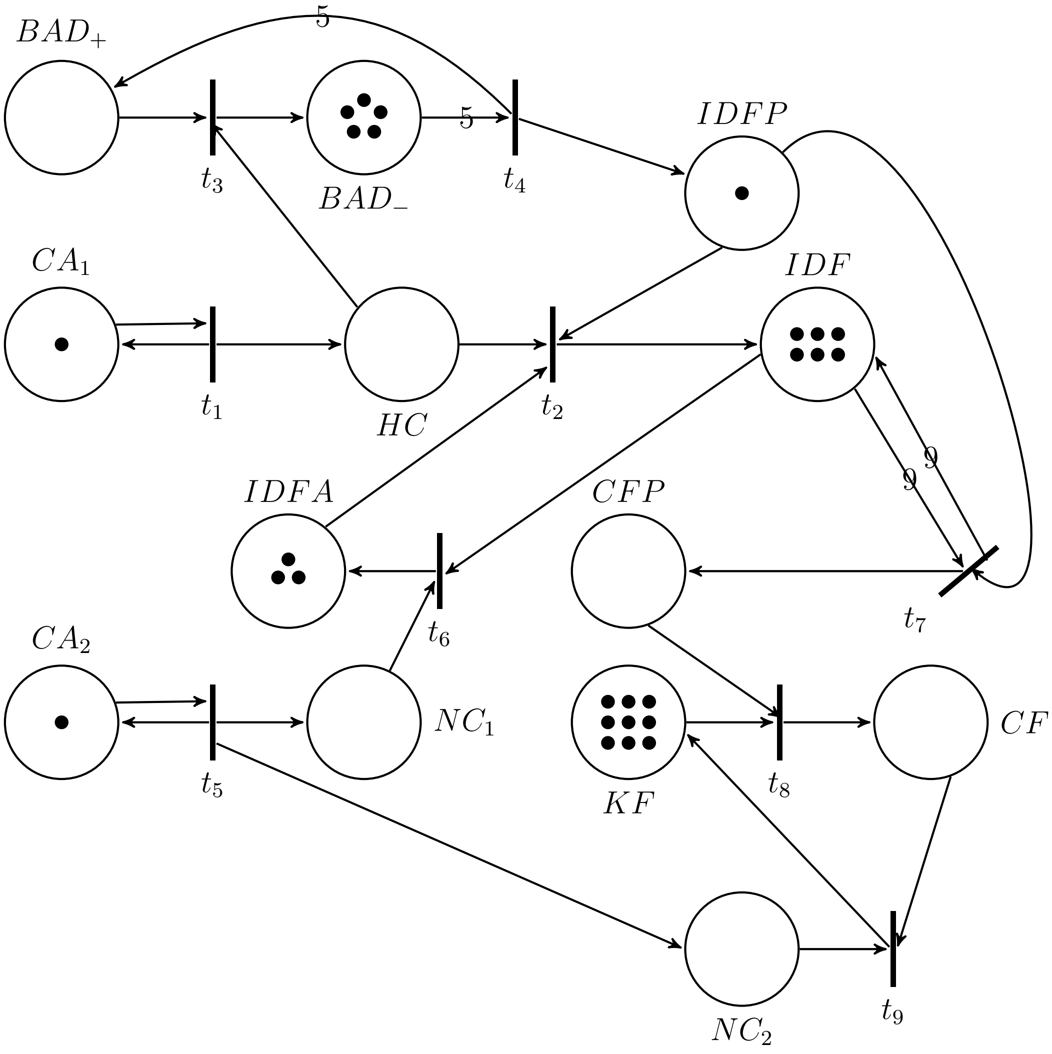

Fig. 3.10.: Kiln CO Petri Net Model

- **$\mathbf{CA_1}$ and $\mathbf{CA_2}$ - CO at Analyzer:** Just like SO_2 and NO_x, CO is also measured at CEMS. Transition t_1 fires when analyzer starts reading higher CO whereas t_5 fires when CO reading at the analyzer drops back to the normal emission range. Both t_1 and t_5 respectively send a token at HC and NC state.

- **HC - High CO:** A token in this place represents that kiln is at high CO emission state and an action is needed to bring emission down.

- **$\mathbf{NC_1}$ and $\mathbf{NC_2}$ - Normal CO:** A token in this place represents that kiln came back to normal CO emission state following a high CO emission state.

- **CFP - Cut Fuel Permissible:** A token here allows to cut the fuel to the kiln.

- **$\mathbf{BAD_+}$ - Open Bleed Air Damper:** Bleed air damper increase in-leakage air into the kiln. A token in this place represents that bleed air damper is opened and kiln is at higher in-leakage state.

- **$\mathbf{BAD_-}$ - Close Bleed Air Damper:** In-leakage air into the kiln is reduced by closing the bleed air damper. Token at BAD_- represents what percentage of bleed air damper is closed.

- **IDFP - ID Fan Permissible:** The speed of the ID fan can be increased if $IDFP$ has a token. This permission comes from the fact that bleed air damper is closed 100% and only option to increase the draft inside the kiln is by increasing ID fan speed

- **IDFA - ID Fan Available:** Tokens at $IDFA$ represent the percentage of ID fan available to the kiln.

- **IDF - ID Fan:** Tokens here represents the current speed of the ID fan in terms of percentage. Sum of IDF and $IDFA$ should be equal to 100%.

- **$\mathbf{NC_1}$ and $\mathbf{NC_2}$ - Normal Carbon:** Token at the place NC shows that the kiln is back into normal CO emission state followed by a higher CO emission state.

3.6 Analysis of SO_2 Petri Net Model

Further analysis of SO_2 is discussed in detail in this section. Similar analysis can be performed on NO_x and CO Petri net models also. Initial state for the Figure 3.8 is given as,

$$M_0 = \begin{bmatrix} 1 & 0 & 1 & 9 & 0 & 9 & 0 & 0 & 9 & 0 & 9 & 0 & 0 & 0 & 5 & 0 & 1 \end{bmatrix}^T \tag{3.9}$$

Equation 3.9 represents kiln at its full capacity under normal SO_2 emission condition. If CEMS reads higher sulfur, transition t_1 is going to fire and the state of the kiln will change. A sequence of firing transitions and subsequent kiln states are given on next page.

$$\begin{array}{c}
\begin{bmatrix} 1 & 0 & 1 & 9 & 0 & 9 & 0 & 0 & 9 & 0 & 9 & 0 & 0 & 0 & 5 & 0 & 1 \end{bmatrix}^T \\
\Big\downarrow t_5 \\
\begin{bmatrix} 1 & 1 & 1 & 9 & 0 & 9 & 0 & 0 & 9 & 0 & 9 & 0 & 0 & 0 & 5 & 0 & 1 \end{bmatrix}^T \\
\Big\downarrow t_1 \\
\begin{bmatrix} 1 & 0 & 1 & 8 & 1 & 9 & 0 & 0 & 9 & 0 & 9 & 0 & 0 & 0 & 5 & 0 & 1 \end{bmatrix}^T \\
\Big\downarrow t_{10} \\
\begin{bmatrix} 1 & 0 & 1 & 8 & 1 & 9 & 0 & 1 & 9 & 0 & 9 & 0 & 0 & 0 & 5 & 0 & 1 \end{bmatrix}^T \\
\Big\downarrow t_2 \\
\begin{bmatrix} 1 & 0 & 1 & 8 & 0 & 8 & 1 & 0 & 9 & 0 & 9 & 0 & 0 & 0 & 5 & 0 & 1 \end{bmatrix}^T \\
\Big\downarrow t_3 \\
\begin{bmatrix} 1 & 0 & 1 & 8 & 0 & 8 & 0 & 0 & 8 & 1 & 8 & 1 & 0 & 0 & 5 & 0 & 1 \end{bmatrix}^T
\end{array}$$

In above firing sequence of kiln events, last state has lower raw feed, RPH and ID fan speed. Based on the marking of last state Equation 3.10 shows the calculation of real values based on Petri net state,

$$\begin{aligned} Raw\ Feed &= M(P_6) \times 80 = 640\ liters/minute \\ Kiln\ Speed &= M(P_9) \times 9.6 = 76.8\ rph \\ ID\ Fan\ Output &= M(P_{11}) \times 11 = 88\% \end{aligned} \tag{3.10}$$

As per Equation 3.10, the kiln is operating at a reduced production rate due to high sulfur emissions. In the sequence, transition t_2 fired instead of t_9 because of the order of priority. When two transitions are enabled simultaneously a priority is assigned to make a decision on the next action. In Figure 3.8, transition t_2 and t_9 are only two transitions that can get enabled simultaneously and firing of one of them disables another. Based on the control strategy t_2 takes priority over t_9. If sulfur remains high for a longer period of time, kiln fuel will gradually move from FQW to natural gas. After getting 100% natural gas ON to the kiln if sulfur emission does not go down the Peri net model will start cutting down kiln feed. Eventually feed will be completely off and kiln will reach into the preheat state.

3.7 Dynamics of SO_2 Petri Net Model

As per the definition of enabled transitions and based on the Figure 3.8, transitions t_5, t_6 and t_{10} are enabled initially. But none of these transitions are going to fire unless initiated by analyzer. Firing of these transitions is prompted by the emission reading at analyzer. Although SO_2 emission modeling is a timed Petri net, all four timed transitions are firing independently and timing of their fire indirectly depends on the quality of fuel and kiln feed. Maintaining a uniform kiln feed is a major challenge for cement plants and many times it is impossible to achieve because quarry limestone variability is not in human control. Uniformity is achieved by blending the kiln feed tanks or by agitating a larger tank. In either case despite of all the efforts to maintain feed uniformity, kiln feed sample shows difference in quality with time. Hence it is not possible define a clock structure of the timed transitions. Also at the same time their timing is not a random variable because it depends on certain input variables. Timed transitions does not change the flow of tokens in the Petri net model rather they simply delay the transition of model from one state to another.

After comparing the input and output weights of the states in Figure 3.8. input and output incident matrix, B^- and B^+ are obtained as shown in Equations 3.11 and 3.12 respectively. Later incident matrix B is calculated using Equation 2.6. With the help of the incident matrix B and initial state M_0 next state can be calculated using state Equation 2.10.

$$B^- = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{3.11}$$

$$B^{+} = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{3.12}$$

Initial state of the model is,

$$M_0 = \begin{bmatrix} 1 & 0 & 9 & 9 & 0 & 9 & 0 & 0 & 9 & 0 & 9 & 0 & 0 & 0 & 5 & 0 \end{bmatrix}^T \tag{3.13}$$

Theoretically any transition out of t_5, t_6 and t_{10} can fire. Suppose transition t_{10} fires first, then as per Petri net state equation, the firing vector is,

$$x_{10} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.14}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{3.15}$$

With the help of Equation 2.10 next state M_1 is calculated as,

$$M_1 = \begin{bmatrix} 1 & 0 & 9 & 9 & 0 & 9 & 1 & 0 & 9 & 0 & 9 & 0 & 0 & 0 & 5 & 0 \end{bmatrix}^T \tag{3.16}$$

M_1 is the state of the kiln when feed to the kiln has higher sulfur and it is allowed to reduce the feed on the kiln. With the use of B, M_0 and x_k future states of the kiln can be calculated in the similar manner.

4. DESIGNING EMISSION CONTROLLER USING PETRI NET

All the examples in this Chapter are in context with the Petri net model of SO_2 emission given in Figure 3.8. An understanding of some more Petri net concepts is needed in order to design a controller [8], [9]. In next two sections concept of place invariant and transition invariant is discussed [8].

4.1 Place Invariant

For a given Petri net N if $\exists$ a X such that,

$$X^T M_i = constant \; \forall \; M_i \; \in \Re(N) \tag{4.1}$$

then vector X is said to be a place invariant for the Petri net N. Here, $\Re(N)$ represents all the states that the Petri net N can reach. Equation 4.1 can be rewritten as,

$$X^T M_i = constant \implies X^T M_0 = X^T M_{k+1} \tag{4.2}$$

Recall the standard Petri net state equation,

$$\begin{aligned}
M_{k+1} &= M_k + Bx_k \\
\implies M_1 &= M_0 + Bx_0 \\
\implies M_2 &= M_1 + Bx_1 \\
\implies M_2 &= M_0 + B(x_0 + x_1) \\
&.. \\
&.. \\
\implies M_{k+1} &= M_0 + B\sum_{j=0}^{k} x_j
\end{aligned}$$

We can rewrite the above equation as,

$$M_{k+1} = M_0 + BV_k \tag{4.3}$$

where, V_k is called characteristic vector. The value of V_k tells us how many times a transition is fired in a Petri model to move from state M_0 to M_{k+1}. Upon premultiplying the Equation 4.3 by X^T we get,

$$X^T M_{k+1} = X^T M_0 + X^T BV_k \tag{4.4}$$

If X^T is a place invariant for a given Petri net with incident matrix B then,

$$X^T M_{k+1} = X^T M_0 \implies X^T B = 0 \tag{4.5}$$

Hence the condition for X^T to be a place invariant is given in the Equation 4.6.

4.2 Transition Invariant

With reference to Equation 4.3 if,

$$BV_k = 0$$

then V_k is known as transition invariant. It is evident by its name that initial and final states are same after a sequence of firing transition. Mathematically,

$$M_{k+1} = M_0 \tag{4.6}$$

4.3 Petri net controller

Assume that there is no extreme change in sulfur emission and $w(s)$ in SO_2 emission Petri net model is always 1. Thus delay of transition t_5 becomes a constant value of 5 minutes. kiln high emission state can be eliminated if tokens in the state HS can be restricted under 2. Thus, kiln fuel place KF will not lose more than 2 tokens. Therefore it is desired that,

$$M_{HS} \leq 2 \tag{4.7}$$

Equation 4.7 is known as state based control criterion and controller thus obtained is called state based controller. Generalized form of Equation 4.7 would be,

$$L * M \leq b \tag{4.8}$$

where,

L is $n_c \times n$ matrix representing all the states that has restrictions on them

M is $n \times 1$ vector which represents the places that are part of the constraints

b is $n_c \times 1$ vector has the values of all the imposed constraints and,

n_c is the number of constraints

Equation 4.8 can be modified as,

$$L * M + M_c = b \implies \begin{bmatrix} L & I \end{bmatrix} * \begin{bmatrix} M \\ M_c \end{bmatrix} = b \tag{4.9}$$

Equation 4.9 is a state invariant condition and using the Equation 4.6 we obtain the condition for place invariant as follows,

$$\begin{bmatrix} L & I \end{bmatrix} \times \begin{bmatrix} B \\ B_c \end{bmatrix} = 0$$

$$\implies LB + B_c = 0$$

$$\implies B_c = -LB$$

As per SO_2 emission model given in the Figure 3.8,

$$L = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{4.10}$$

Thus controller state can be calculated as,

$$B_c = -\begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \times$$

$$\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\
1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\
0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\
0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0
\end{bmatrix}$$

$$\Longrightarrow B_c = \begin{bmatrix} -1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The controller place p_c has one output arc going to transition t_5 and one input arc from transition t_1. Using Equation 4.9 initial state of controller place is calculated as,

$$\begin{aligned} L * M_0 + B_{C0} &= b \\ \Longrightarrow B_{C0} &= b - L * M_0 \\ \Longrightarrow B_{C0} &= 2 - 0 = 2 \end{aligned} \tag{4.11}$$

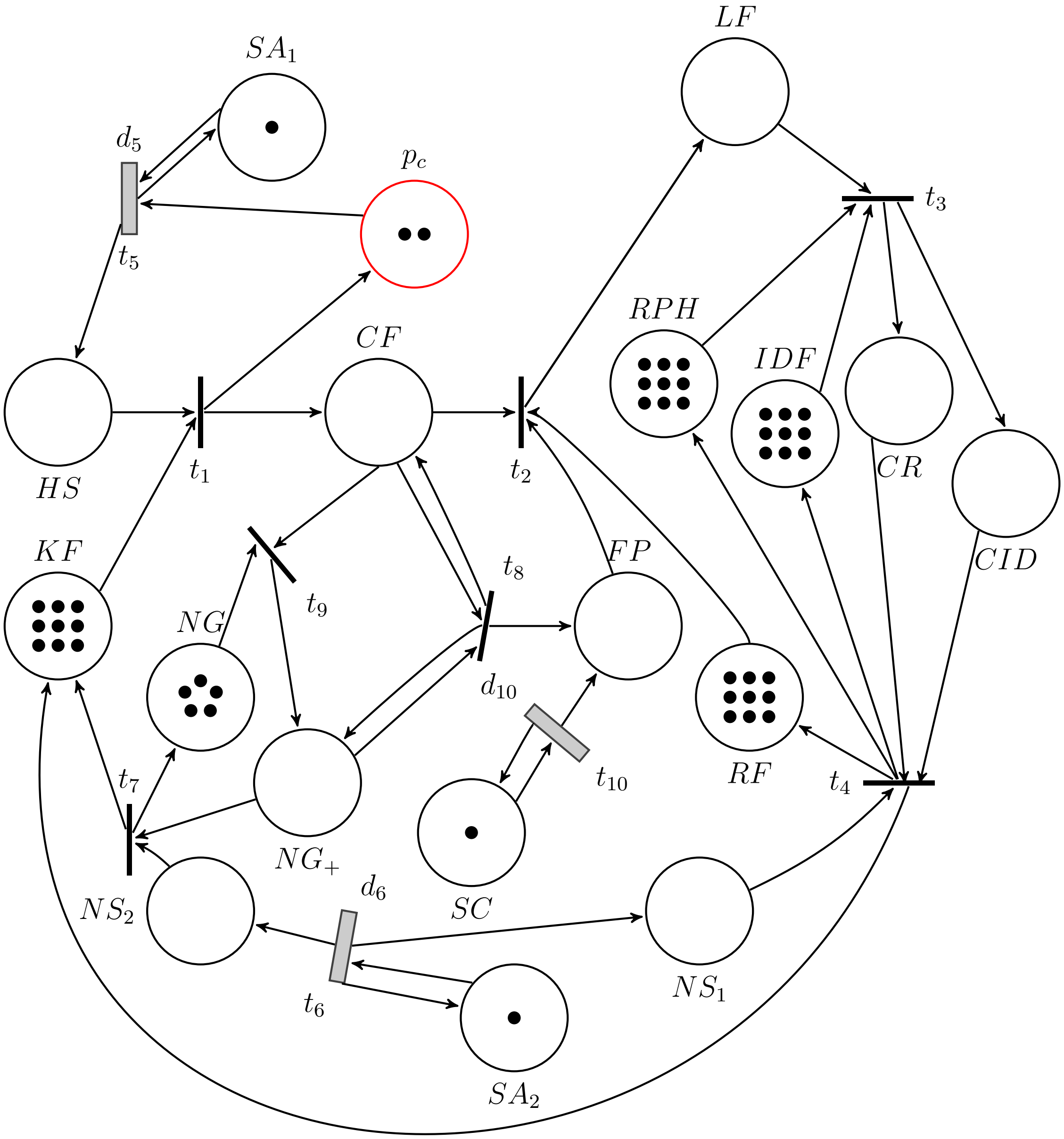

Fig. 4.1.: Kiln SO_2 Petri Net Model with controller

In Figure 4.1, P_c is the controller state. Because of p_c, t_5 cannot fire more than 2 times and that will leave HS with at most 2 tokens. Hence transition t_1 also cannot fire more than twice and cannot move more than 2 tokens from the state KF to CF.

5. FUTURE WORK

In Chapter 4, place p_c in Figure 4.1 can limit the tokens in the HS place but in the real world, it is very difficult to have a place like p_c that can control the high sulfur state of the kiln. This limitation of real world application makes it hard to implement a Petri net controller that we have designed the previous Chapter. But if there is a technique that can estimate the sulfur reading at the analyzer based on the input to the kiln and conditions inside the kiln, a proactive control measures can be taken. Thus the Petri net model in the Figure 3.8 combined with the estimation of SO_2 at the analyzer will make it much easier to implement in a cement plant.

In the case of kiln emissions, a neural network can be used estimate analyzer's values. The neural network can be trained based on the trends given in Chapter 2. A well trained neural network can estimate a close value of analyzer emission value and an action can be taken based on the value obtained from a neural network instead of waiting for a value from the analyzer. The reading at the analyzer is after the fact value and by the time an action is taken based on analyzer readings kiln has already reached a higher emission state. Thus, the use of neural network along with the Petri net model will evolve into a better control of kiln emission. The work in progress is to train a neural network with 2 hidden layers using error based back propagation weight update method.

To match the Petri net state markings close to the real values, more tokens can be used in each place. This will reduce the impact on the kiln parameter value when a token is moved as a result of transition firing. A continuous Petri net model can also provide a real time analysis of the dynamics of emissions [10].

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