# Investigation of critical failures using root cause analysis methods: Case study of ASH Cement PLC

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## Abstract

Like other modern day process industries, most cement manufacturing operations are continuously sorting after state-of-the-art failure identification and analysis approaches that can help avert the reoccurrence of failures, owing to the huge costs of downtime associated with critical plant assets such as the rotary kilns. Research-based investigation of the root causes of high impact failures of critical industrial assets have been dominated by the use of complex mathematical methods for analysing experimentally and numerically simulated scenarios. While the academic contributions of such approaches is highly commendable, the potential of deploying them to the industry as well as their ability to simulate experiential learning is significantly lower than when "real life" industrial case studies are used. Through the application of a fully integrated cement plant located in Northern Nigeria as case study; this paper employs two popular risk analysis techniques (fault tree analysis and reliability block diagram) to detect the causal factors as well as their interrelations of a chronic rotary kiln refractory brick failure. Unlike the previous plant-based investigations which continuously attributed the failure causes to refractory brick design/manufacturing, the current approach provides a detailed, almost macroscopic dimension of vulnerabilities in maintenance, operations and quality practices in the plant. Through a combination of theory and immense practical knowledge of the case study plant, the current investigation team also provided several vital and realistic recommendations that could eliminate or significantly reduce the possibility of kiln refractory brick failure in the plant. The cornerstone of this paper is not to undermine the currently used Apollo method of root cause failure analysis in this cement plant, but rather to provide a complementary holistic approach to the investigation

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of critical failures. Therefore, the robustness of in-plant failure analysis can be enhanced through effective integration of the individual approaches.

**Keywords:** Fault tree analysis, Reliability block diagrams, Critical failures, Cement rotary kiln

## Introduction

For so many decades, a significant number of process plants have relied heavily on rotary kilns for the achievement of their manufacturing objectives. Rotary kilns can be described as calcinations devices that facilitate chemical or physical transformations by subjecting materials to very high temperatures (also known as pyroprocessing). A classical example of rotary kiln operation is in the production of clinker (the main ingredient for manufacturing cement), whereby pulverised raw materials (mainly limestone, alumina, sand and iron ore) mixture undergoes calcinations at temperatures in excess of $1500^{o}C$ [1]. Other vital industrial operations that involve rotary kilns include the production of lime, iron pellets, alumina, etc. [2-3]. Just like every other critical industrial asset, rotary kiln system functions are often associated with various performance standards including runtime (e.g. continuous operation or required availability), physical integrity, operational performance quality and tolerance, etc [4-6]. The satisfactory achievement of these performance standards is considered system success while deviations from one or more of them are termed system failure. To further illustrate this, Figure 1 presents a graphical illustration of failure and success as described in an earlier study by Rausand and Oien [6]. According to the figure, once an asset is commissioned, performance targets are set (set target) so as to monitor operational success or failure. In order to minimise disruptions to day-to-day operations, the asset performance is sometimes allowed to float within a certain limit (stretch and lower acceptable targets). On the one hand, the region between the stretch and lower acceptable target represents the success region. The point at which performance begins to drop below the acceptable limit is considered failure and the region representing such performances over time is the failure region.

In general, both success and failures always provide immense lessons through which organisations can either replicate favourable performances or avoid the reoccurrence of previous errors. While literatures based on conventional teachings strongly advocated the strengths of learning from internal and external successes [7-8], relatively recent studies [9-11] have argued that organizations are more likely to learn from failures than success. This is perhaps based on the premise that splotches caused by failures are more likely to trigger the conditions required for sustainable experiential learning [12-13].

Over the years, researchers have continuously attempted to investigate the root causes [14-16] of engineering failures using different approaches. For instance, Otegui et al. [17] conducted a case study based investigation of the common root causes of weld joints failures in industrial pressure vessels using finite element and mechanical stress analyses. Based on the investigation of three distinct cases, the study [17] deduced that increasing the thickness of welds as a means of enhancing the factor of safety significantly increased cyclic stress due to excess pressure vessels weights. In an attempt to further understand the behaviour and root causes of crack failure in critical industrial machines such as turbines, the studies by Ataya and Ahmed [18]; Silveira et al. [19] and Sz et al. [20] respectively examined blade cracks in wind, aircraft and steam turbines. In the former study on blade cracks [18], 98 wind turbine blades were investigated and it was observed that transverse cracks are often associated with the high fatigue loaded regions of the blade trailing edge. Through the application of various health monitoring techniques including stress analysis (mechanical and thermal); natural frequency calculations; metallurgical examination and fractography, Silveira et al. [19] attributed blade failures in high pressure turbines of aircrafts to thermal-mechanical fatigue. On the other hand, study by Sz et al. [20] on a 350 MW steam turbine ascertained that excessive tolerances between blade root and root fastening tree leads to stress concentration in the blade root which can initiate cracks. In other studies, Chen et al. [21] investigated the fault features of cracked planetary gears using analytical mesh stiffness models while Escobar et al. [22] detected stress corrosion cracks in the assembly bolts of submersible pumps using mechanical and optical test methods. Similarly, Domazet et al. [1] developed finite element models in order to study the stress distribution and the location of fatigue cracks in cement mill girth gears. Murugan and Ramasamy [23] used statistical methods to analyse power transformer failures with respect to voltage levels, geographical locations and component failures.

As valuable and relevant as the findings from these failure detection methodologies [17-23] are their thumping computational and mathematical requirements sometimes hamper deployment to the industry. Additionally, they are mostly based on experimental and theoretically simulated scenarios which may or may not directly represent “real life” industrial scenarios. Based on these premises, the continuous application of engineering analysis techniques that can systematically show the causal relationships that exist between complex industrial events (success or failure) is long overdue. Fault tree analysis (FTA) and reliability block diagrams (RBD) are some of the most illustrative and commonly used performance assessment techniques within the last five decades. Their applications span across various industries including nuclear, aerospace, military, manufacturing, oil and gas, etc. Purba [24] used fuzzy based reliability approaches for evaluating the basic events of a nuclear power plant fault tree. Similarly, Lavasani et al. [25] discussed the applicability of FTA to oil and gas offshore pipelines by analysing the root causes of a Deethanizer failure which identified fire, explosion and toxic gas release as potential hazards. Cong et al. [26] also proposed FTA for on-line repair of damaged pipes in petrochemical plants. Other studies [13, 27] have also used FTA and RBD techniques for analysing historic engineering catastrophes such as Fukushima nuclear disaster, Titanic, BP Texas city incident, Chernobyl disaster, Bhopal disaster, and NASA space shuttle Columbia accident.

It is undeniable that significant amount of work has been performed with FTA and RBD techniques. However, very few cases of their applications in vital manufacturing plants such as cement, steel, automotive, textiles, etc., currently exists in the literature. Some of the few works include the application of FTA for assessing premature failures in the induced draft fan of a cement process plant, which was attributed to the inadequate insulation of the induction motor winding [28]. Li et al. [29] also used FTA to analyse various failure modes associated with cement rotary kiln axis alignment system. More recently, Gharahasanlou et al. [30] showed how FTA can be used to detect the failures associated with the crushing plant and mixing bed hall of a cement plant. Since the cement rotary kiln is the single most valuable asset of any fully integrated cement process plant, the current study is based on the combination of FTA and RBD for the analysis of a chronic rotary kiln insulation brick failure of a cement plant located in Northern Nigeria (ASH Cement PLC). The paper presents how the application of FTA and RBD can systematically show the causal relation between the various elements of a complex industrial failure, which is very vital for the prevention of reoccurrences.

## 2. Overview of fault tree analysis and reliability block diagrams

The concepts of FTA and RBD have existed for decades and are well-known across various industries especially nuclear and aerospace. Despite the long standing establishment of these valuable engineering failure analysis tools, research studies [27-28] indicate that their applications have been significantly skewed towards systems design failure analysis and very little in the area of industrial asset operation and maintenance management. Through the application of a cement manufacturing company as case study, the current paper attempts to provide a holistic approach to failure analysis using FTA and RBD. Just like any other engineering tool, FTA and RBD have enjoyed their fair share of criticism particularly in the area of not being able to capture interdependence among failure modes, and reducing complex problems into simple root cause analysis. However, recent research has also provided guidelines on how to overcome these limitations as well as provided best practice in constructing the FTA and RBD models [31]. Also, a recent study by Labib and Read [32] shows how to integrate the FTA and RBD modelling to multiple criteria decision making techniques such the Analytic Hierarchy Process (AHP) and demonstrated the use of such a hybrid approach in studying the Hurricane Katrina Disaster. It is therefore hoped that the approach discussed in this paper will further enhance existing methods, so that chronic failures in this plant as well as others can be effectively minimised.

### *2.1 Fault tree analysis (FTA)*

Fault tree analysis (FTA) is a systematic “top-down” failure analysis technique that gradually progresses deductively from the emergence of an unwanted event (also known as the “top event”) to the identification of the causal factors (also known as “basic events”) of that particular unwanted event [27]. Besides identifying the root causes of the unwanted event, FTAs can equally show the causal relationships (using logic gates) that exist between them which can help both equipment designers and operators understand how components/systems can fail. The construction of a typical fault tree commences with the “top event” which is usually chosen based on its criticality to the studied system. Once the “top event” is defined, the next stage of the construction is to determine all its possible causes and then connecting them with appropriate logic gates. The events of a typical fault tree can be connected using a variety of logic gates including AND, OR, k-out-of-n, exclusive OR, inhibit, priority AND, NOT, etc. However, since the majority of problems can be accurately modelled using either

AND or OR gates, the current study will similarly be restricted to the application of AND and OR logic gates. Table 1 shows the different logic gates and symbols that will be used in this paper. In addition to graphically showing the relationships that exist between the various causal factors, the probability of occurrence of the “top-event” can also be obtained. This is usually achieved by estimating the probability of occurrence of the logic gates’ output fault events using Equations (1) and (2) [30];

- OR gate

$$P\left(\boldsymbol{X}_{OR\ gate}\right) = 1 - \prod_{k=1}^{n}\left(1 - P(\boldsymbol{X}_k)\right) \tag{1}$$

Where $n$ denotes the number of input fault events, $P\left(\boldsymbol{X}_{OR\ gate}\right)$ is the probability of occurrence of OR gate’s output fault event $\boldsymbol{X}_{OR\ gate}$ and $P(\boldsymbol{X}_k)$ is the probability of occurrence of input fault event $\boldsymbol{X}_k$ (for $k = 1, 2, 3, \ldots, n$).

- AND gate

$$P\left(\boldsymbol{X}_{AND\ gate}\right) = \prod_{k=1}^{n} P(\boldsymbol{X}_k) \tag{2}$$

Where $P\left(\boldsymbol{X}_{AND\ gate}\right)$ is the probability of occurrence of AND gate’s output fault event $\boldsymbol{X}_{AND\ gate}$

### *2.2 Reliability Block Diagram (RBD)*

A reliability block diagram (RBD) is a logical representation that either depicts the combinations of component failures that would lead to system failure or combinations of adequately functioning components that keep the system functioning [33-34]. In a typical RBD, each block signifies a functional component while any failure is indicated by simply omitting the block that represents the failed component from the diagram. A system represented by an RBD that has at least one path from input to output continues to remain in a functional state and fails once the connection between input and output is completely interrupted [33]. Depending on the system complexity and level of redundancy available, RBDs can have series or parallel configurations. Unlike fault trees that solely focus on the failure combinations of a system, RBDs are particularly concerned with the different combinations of the components in a system that will lead to system functionality [34-37]. During system analysis, an equivalent RBD that indicates system success can be extracted from a fault tree that shows system failure and vice versa. The study by Labib and Harris [27] has already provided clear guidelines on how to effectively convert fault trees to RBDs and vice versa. Additional guidelines on the construction of fault trees and RBDs including ways of overcoming their respective limitations are also provided in a study by Labib [31]. Hence, the equivalent RBDs developed in the current study are mental models extracted from the fault trees so that the visualisation of the different relationships that exist between the causal factors can be simplified. It is crucial to note that the robustness of such techniques with respect to change in data inputs can be assessed at two levels. The first level relates to whether the probability value of each factor has been accurately verified. The second level is about whether the mental model covers all aspects related to the casual factors. We argue that the multidisciplinary nature and experience of the team members involved in the development of the model can ensure that the peer review process enhances the robustness of the technique. So the focus of our approach here tends to be more biased towards the second rather than the first level of assessment. In other words, we agree with the argument posed by Apostolakis [38] in that the importance of risk-informed rather than risk-based decision making should be emphasised.

## 3. The case study

A case study research principally entails the analysis of historical data drawn from various sources of evidence that represent previous or present occurrence(s) within an organisation [39-41]. Because the scopes of case study-based research works are immensely specific, they enable the development of detailed understanding of what is to be studied [42] which can significantly ease the deployment of the concepts to the field. Some authors have questioned the possibilities of generalising case study based research findings as well as the quantity of data often involved [43-44]. However, their ability to simplify the visualisation of “real life” experiences is very vital for the analysis of complex engineering failures [45-46].

In the current paper, the case study is a cement manufacturing plant located in the Northern region of Nigeria (ASH Cement PLC), which has been producing approximately one million metric tonnes of cement per year for over three decades. Cement production in this plant is achieved through the aid of two similarly configured continuously-operating production lines. Each of the production lines is independently equipped with a raw milling, kiln firing, coal grinding, cement grinding and cement packing/discharge stations. While each of the production lines are configured to be significantly independent, common equipment such as raw materials storage silos, cement storage silos, clinker storage silos, utilities, etc still exist. In general, the success or failure of any fully integrated cement process plant is judged by the reliability of its rotary kiln(s), since it produces the main ingredient of cement (i.e. clinker). Hence the rotary kiln is the single most important asset in any cement manufacturing plant. In this plant, each of the rotary kilns has a daily production capacity of 1100 tons of clinker and a dimension of 4 m (diameter) x 72 m (length). The temperature within the rotary kilns is in excess of 1500$^{o}$C so as to adequately effect the combination of the clinker components, especially lime and silica. This high temperature is achieved through the combustion of dual fuel (60% heavy fuel oil and 40% lignite) supplied by a centrally installed high pressure pyro-jet burner. In order to optimise heat generated in the rotary kiln as well as reduce the amount of heat radiated to the steel kiln shell, special heat insulating bricks are used to line the entire kiln interior.

### *3.1 Incidence report and events sequence*

The incident analysed in the current study occurred on line 1 cement rotary kiln. In order to enhance proper understanding of the kiln operation process, the sequence of actions that were taken (from high shell radiation detection to kiln shutdown) as a result of the hotspot on the kiln shell are provided here;

- On 27 April 2012, captured thermal images displayed by the plant supervisory control and data acquisition (SCADA) system showed that cement rotary kiln 1 was experiencing high shell radiation (external shell temperature reached 480$^{o}$C within 2 hours) around the 23 m mark, which is above the acceptable threshold. Figure 2 shows the hotspot at the 23 m mark of kiln 1 as recorded by the SCADA system. In Figure 2, LTZ, BZ and UTZ respectively refer to the lower transition, burning and upper transition zones of the kiln.
- A confirmatory assessment was then conducted using a handheld device and the results also indicated excessive kiln 1 shell temperatures around 21-23 m area.

- Historical operational data (date versus temperature profile) shows that kiln 1 shell temperature reached or exceeded the 400°C upper threshold 15 different times within six weeks as indicated by Figure 3.
- Based on both SCADA and manual shell scan, the kiln operator was then instructed to initiate kiln shutdown procedure, which commenced by reducing liquid fuel quantity from 3230 - 3100 L/h while still maintaining the same raw material feed rate of 74 ton/h. This action significantly reduced kiln temperature since there will be more feed than fuel in the kiln. The solid fuel (lignite) mill was then stopped at 2400 hrs and the solid fuel injection rate was reduced to 2 ton/h. After significant fuel reduction, the raw material feed rate was then reduced from 74 to 68 ton/h. Correspondingly, the rotary kiln speed was reduced from 1.78 to 1.4 rev/min which also led to a reduction of the induced draft fan speed from 700 to 650 rev/min. This gradual kiln parameters (kiln feed, fuel, kiln speed and induced draft fan speed) reduction continued until kiln shutdown at 0600 hrs on 28 April 2012.
- After 24 hrs of cooling, kiln 1 detailed internal inspection commenced on 29 April 2012 at 0900 hrs. The internal inspection revealed that a rectangular refractory brick (0.4 m x 0.8 m) had fallen out from a point that was 23 m from the discharge end of kiln 1 as shown in Figure 4. Other observations from the internal inspection included significantly reduced brick thickness around the area.

### *3.2 Impacts of the incident*

The cement plant used for this case study sits in a sold-out market which implies that the cement demand in that geographical area significantly exceeds supply. Hence, any shortfalls in the cement production/despatch will instantly result to a negative impact on the company’s profitability and competitiveness. Over the 15-day downtime period, approximately £850k loss was directly incurred by the company. This amount includes £680k in lost clinker production plus £170k for spares (e.g. bricks, welding electrodes, bolts, nuts, seals, etc.), labour and hired 150 ton mobile crane.

Besides the estimated direct costs of the failure on sales and maintenance, other aspects of the failure that were not estimated but may have significant long term consequences such as risks of potential litigations from major stakeholders as a result of disrupted cement deliveries arising from enormous despatch backlogs after kiln start up. The economic viability of the immediate community may also be impacted negatively since the dominant business activities in the area are immensely associated with construction materials. Changes to raw materials (e.g. fuel, iron ore, etc.) supply lead time may adversely affect the credit standing of some suppliers with their finance institutions, which could have knock-on effects on the cost and reliability of the supply process. In general, organisations that experience such major manufacturing incidents on frequent basis stand the risk of losing their reputation which may lead to loss of loyal customers to competitors.

### *3.3 Current plant-based failure analysis approach and findings*

In practice, the development of a robust and cost-effective asset management strategy usually entails the integration of several well-known maintenance philosophies. For instance, reactive maintenance (RM) could be allocated to non-critical plant items such as toilet lightings. Planned preventive maintenance (PPM) activities on the other hand can be reserved for plant items with known or predictable failure times while condition-based maintenance (CBM) can be dedicated to extremely critical and randomly failing plant items. However, irrespective of the particular asset management strategy adopted by a company, the competitiveness and profitability of such a company is often affected by how much it is able to learn from costly downtimes as well as implement corrective actions that will prevent reoccurrence. Figure 5 provides a schematic distinction between reactive and continuous improvement based asset management approaches. In the reactive approach, maintenance interventions such as repair or replace are implemented after each failure ($f_1$, $f_2$, $f_3$, …, $f_n$) whereby the continuous improvement based approach incorporates a root cause [47-49] failure investigation element after the first failure ($f_1$) so as to prevent reoccurrence.

In an attempt to trigger a paradigm shift from reactive to continuous and sustainable improvement based asset management, ASH cement plant also thrives to inculcate a culture of investigating the root causes of critical plant failures (e.g. kiln, mills, packers, crushers, etc.) using the Apollo RCA method [50]. In general, the main goal of any effective RCA [47-49] is to identify failure prevention strategies through a systematic process that eventually eliminates blame culture while enhancing safety and overall system effectiveness [49]. The Apollo method of RCA is evidence-based and its process involves failure definition, development of cause and effect chart, solution identification/implementation. The RCAs at ASH cement plant are team-based whereby failure investigations are formally conducted with multidisciplinary teams and a designated RCA facilitator as leader.

For this incident, the core disciplines involved in the RCA were the kiln coach, K1 operators, production shift manager, K1 patrollers, production manager, maintenance manager, kiln section maintenance team lead, methods manager and quality manager. In order to ensure objectivity of the RCA process, the facilitator was the plant safety manager who is neutral to kiln operations. The RCA identified thermal shock due to rapid overheating/sudden cooling, kiln feed variations, unstable kiln coatings and high number of kiln stoppages for incidents (e.g. loss of power and kiln feed losses) as the probable failure causes while refractory brick quality was adjudged to be the main root cause. Hence refractory brick replacement was the recommended correction action. Just like other RCA methods, a key success factor is the prevention of failure reoccurrence. However, this as well as the previous RCAs for K1 brick failure has not achieved this aim since similar failures have hampered clinker production at ASH cement plant 10 times within 9 years, with each of the incidents leading to at least 14 days of plant downtime. Based on this premise, the current study investigates the same K1 refractory brick failure using a combination of two alternative failure analysis techniques. During the analysis, the same RCA team were consulted and similar plant evidences were used but in more detail. It is worth mentioning that the main aim of the current paper is not to undermine the Apollo method of RCA but rather explore the robustness of other failure analysis approaches such as FTA and RBD, so as to offer alternative platforms through which cement and other manufacturing companies can further ascertain the effectiveness of their existing methodologies.

## 4. Kiln 1 Brick Failure Investigation with FTA and RBD

Plant failure data obtained from the advanced downtime analysis program (ADAP) at ASH Cement Company showed that K1 refractory brick failure has occurred ten times within nine years with each of the failures accounting for no less than 14 days of plant downtime. Based on these statistics and the cost implication of the failures, it is logical to regard K1 refractory brick failure as chronic. A thorough review of ADAP data for the periods covering the ten K1 refractory brick failures identified three main classes of probable causes, namely: (a) poor K1 maintenance, (b) poor K1 operation and (c) poor K1 quality. The selection of the three classes was also validated based on at least ten years of practical experience of one of the authors of this paper with the operations, maintenance and safety departments of ASH Cement Company as well as the combined industrial experiences of the plant-based investigation team. Figure 6 shows a global FTA of the three main probable causes. Due to the chronic nature of these particular failures, initial fault trees developed for all three main classes of probable causes were generic so that it can be used beyond the investigation of the current failure (especially when considering future design improvements, risk assessments, plant team trainings, etc.) as FTA for complex industrial processes can be time and resource consuming. From the generic fault trees, resultant fault trees were then generated by eliminating events that did not contribute to the K1 failure that occurred on 27 April 2012.

### *4.1 Generic FTAs for K1 refractory brick failure*

In order to enhance clarity, each of the identified classes of probable causes was independently developed as shown in Figures 7-9. In Figure 7, a detailed analysis of plant data for ten K1 brick failure incidents showed that the poor maintenance probable cause (A) was mainly associated with K1 burner pipe misalignment (IA1). When a cement kiln burner pipe is misaligned, heat from the flame (approximately 1800°C) becomes skewed towards certain sections of the burning zone which eventually wears out the protective coatings for the refractory bricks at those sections. Once the coating is lost, the refractory bricks become subjected to direct heat from the flame which then leads to premature failure. IA1 can be due to either inaccurate alignment during previous shutdowns (a1) or excessive K1 vibration during normal operation (IA2). Based on observed plant failure data, it was ascertained that the main causes of the IA2 event are failure of K1 induced fan damper (IA3) or worn K1 tyre and support rollers (IA4). Further investigations indicated that the dominant causes of IA3 are programmable logic controller (PLC) failure (UA1), stiffness of induced draft fan damper arm due to lubricant failure (IA5) or inadequate power cylinder operating pressures (IA6). The lubricant failure is commonly due to a combination of excessive heat around the damper arm bearings (a3) and heat shield failure (a4) or ingress of dust as a result of damaged damper arm bearing seals (a2). The major causes of IA6 on the other hand is either failure of the instrument air compressor (a6) or a significant drop in the instrument air pressure due to leakages along the line (a5). Similarly, K1 vibrations due to worn K1 tyres/support rollers

(IA4) was adjudged to be caused by overheating of tyre and roller (IA7) due to cooling system failure (a7) or poor lubrication between tyre and support rollers (IA10).

The production of high quality cement in a cost-effective manner significantly depends on how well the rotary kiln operational and quality parameters are managed. A slight deviation from any of these parameters usually leads to costly plant downtimes such as K1 refractory brick failure. The generic fault trees in Figures 8-9 respectively show the basic events associated with poor K1 operation and quality control activities. The production logs for the ten K1 brick incidents showed that poor operation (Figure 8) probable cause is either due to thermal shock (IB1) or kiln disturbance (IB2), while IB1 is a function of lack of adherence to K1 ramp-up (b1) and ramp-down procedures (b2). Kiln disturbance on the other hand is often caused by either any of the following:

- Loss of K1 feed (IB5) due to either lack of material in silos (b3) or extraction difficulties (IB9) associated with air slides (b5), silo blockage (b4) or lack of extraction air (IB13).
- Loss of K1 fuel (IB6) is either associated with loss of solid (lignite) fuel loss (IB10) or liquid (HFO) fuel loss (IB11). Further breakdown of IB10 shows that the base events are lignite mill failure (b8), lignite shortage (b9), lignite transport pump failure (b10) or lignite storage hopper failure (b11). Similarly, IB11 base events are HFO shortage (b12), HFO pumps failures (b13 and b14), HFO delivery pipe blockage/damage (b15), boiler failure (b16), steam pipe connector failure (b17) or damaged steam pipes (b18).
- Loss draft (IB7) through K1 as a result of induced draft fan failure (b19).
- Loss of K1 rotation (IB8) due to failure of K1 gearboxes (IB18 and IB19), drive motor failure (IB12), main drive coupling failure (b24) or loss of power (b23).

Poor K1 quality (Figure 9) was adjudged to be generally associated with either inaccurate K1 design/manufacture (IC2) or non-homogenous K1 feed (IC3). IC3 can either be related to poor K1 refractory specifications (UC1), poor K1 shell metal specifications during design/manufacture (UC2) or loss of K1 poor concentricity (UC3). Feed to K1 is a mixture of four main raw materials (i.e. limestone, iron ore, alumina and river sand), which must be accurate metered in order to effectively produce high quality cement. The metering is performed by four similarly designed and configured weighing systems with exactly same failure modes. Hence, their common base events are load cells failure (i.e. c4, c6, c8 or c10), torn weigh belts (c5, c7, c9 or c10), failed tracking rollers (i.e. c12, c16, c20 or c24), belt tension bolts failure (i.e. c13, c17, c21 or c25), damaged tail drum pads (c14, c18, c22 or c26) or damaged head drum pads (c15, c19, c23 or c27).

## *4.2 Resultant FTAs for K1 refractory brick failure*

The resultant fault trees displayed in Figures 10-12 are extracts from the generic fault trees but rather than incorporating all the possible causes of K1 failures over nine years, only the events that contributed to K1 refractory brick failure of 27 April 2012 were considered. It is vital to note that the construction of the resultant fault trees through the elimination of non-contributory events in the generic fault trees is purely based on evidence. For instance, the resultant fault tree for poor maintenance (Figure 10) only consists of basic events a2-a6 while a1, a8-a10 and UA1-UA4 were all eliminated. These omissions were based on the favourability of K1 burner pipe alignment (a1) results prior to start-up after previous shutdown and CMMS data showed that there were no downtimes due to PLC failure (UA1) or worn/cracked K1 tyres and support rollers (a8-a10 and UA2-UA4).

Similarly poor K1 operation resultant fault tree (Figure 11) only considered basic events b1-b7 while events b8-b40 were all eliminated. The production log sheet for the period preceding the 27 April 2012 incident showed that the K1 ramp-up (b1) and ramp-down (b2) varied between different shift operators. The plot of K1 temperature profile over six weeks (Figure 3) also showed that the shift operators barely achieved the recommended K1 shell temperatures. Another observed loophole in K1 operation is the lack of proper management of K1 feeding system, owing to several instances of storage silo extraction difficulties (b4 and b5), empty storage silos (b3) and inadequate extraction air (b6 and b7). Loss of feed to K1 under steady fuel and air supply implies that the possibility of premature brick failure is significantly increased since there is no feed to take up the excess heat.

For poor quality (Figure 12), design and manufacturing considerations such as K1 shell concentricity (UC1) and axial run-out (UC2) were eliminated based on the premise that the results of previous structural integrity measurements (Figure 13) showed maximum non-concentricity and axial run-out values of 0.3 mm and 0.55 mm respectively, which are well within the acceptable limits. Once quality issues related to design/manufacturing are eliminated, the focal point then shifts towards non-homogeneity of the feed (IC3) which were mainly attributed to inadequate blending (c1-c3) and the failures of raw materials weighing systems (c4-c27). The adverse effects of c1-c27 is on the fluctuations of key quality parameters such as lime saturation (LSF) and coating (CF) factors as shown in Figure 14. LSF is a measure of the lime content of kiln feed. In essence, the higher the LSF, the greater the percentage of un-combined lime which will require additional heat energy to burn. While it is recommended to maintain substantial LSF values, it is crucial to control the amount of free lime due to its ability to continuously trap moisture and cause cracks in cement structures. Looking at Figure 14(a), LSF values within the six weeks preceding K1 brick incident constantly exceeded the target values. The CF shown in Figure 14(b) is a measure of how well K1 refractory bricks in the burning zone are protected by the layer of coating formed by molten clinker. For CF, the plant's target of 26-30 was not maintained.

The success of FTAs is a function of the familiarity of the failure investigation team, which is perhaps the reason why there is a brainstorming element to most FTAs. RBDs on the other hand provide a means of further exposing the interactions between the various causal elements so that system vulnerabilities can be easily identified. For each the resultant fault trees (Figures 10-12), an equivalent RBD (Figures 15-17) was also developed based on the rules defined by Labib and Harris [27]. In addition to the individual RBDs, a global RBD that integrates the individual equivalent RBDs is also shown in Figure 18 so that the interface between the different classes of failure causes can be easily visualised. The integrated RBD depicts a very fragile interaction between the different events, owing to the significant number of associated series structures. The causal factors in the RBD are mostly related to the poor culture of maintenance and operations in the plant, although it can also be argued that a more recent K1 burner pipe design with deflection measurement capabilities will aid the early detection of misalignment.

## 5. Recommendations from the failure investigation team

A significant number of the current investigation team members were also involved in the initial failure investigation using the Apollo method. However, unlike the earlier exercise that purely dwelled on external factors (outward-looking) such as brick design and therefore recommended the usual action of refractory brick replacement, the current investigation based on FTA and RBD provided more insights about inherent lapses in the maintenance, operation and quality practices within the plant. Therefore, Table 2 provides an action plan that encompasses vital recommendations that could effectively minimise future occurrence of the chronic K1 refractory brick failure at the case study plant.

## 6. Conclusions

In general terms, failures of critical industrial assets can either be attributed to how the asset was made (design integrity) or its usage (maintenance and operation management strategy). Systems analysis techniques such as fault tree analysis (FTA) and reliability block diagram (RBD) have been immensely used to generate valuable lessons from crucial industrial failures. However, the current body of literature depicts that most of the applications of these techniques focus on the assessment of design risks and far less of operation and maintenance. Using a case study cement plant, the current paper performs qualitative FTA and RBD analysis for a chronic rotary kiln refractory brick failure. While the case study cement plant has an already established failure investigation approach based on Apollo method of RCA, it was observed that the outcomes of their analysis have been unable to prevent future occurrences. Using FTA and RBD techniques, a cross-functional investigation team comprising of vey experienced engineers in the case study plant as well as academics have provided a more holistic understanding of the failure causing factors and their interrelations. The investigation team also provided various relevant and realistic recommendations that could either eliminate or significantly reduce the occurrence of kiln refractory brick failures.

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## Appendix 1. Basic events

| | |
|---|---|
| a1 | burner misaligned from installation |
| a2 | bearing seal failure |
| a3 | excessive operating temperature |
| a4 | heat shield failure |
| a5 | compressed air line leakage |
| a6 | instrument air compressor failure |
| a7 | cooling system failure |
| a8 | graphite replacement interval too long |
| a9 | graphite holder failure |
| a10 | improper graphite storage |
| b1 | operator did not follow ramp-up procedure |
| b2 | operator did not follow ramp-down procedure |
| b3 | feed silo empty |
| b4 | feed silo canvas blockage |
| b5 | extraction air slides blockage |

| | |
|---|---|
| b6 | leakage along extraction air line |
| b7 | extraction blower failure |
| b8 | lignite mill failure |
| b9 | shortage of lignite supply to mill |
| b10 | mill-to-K1 lignite transport pump failure |
| b11 | lignite storage hopper blockage |
| b12 | heavy fuel oil (HFO) supply shortage |
| b13 | HFO pump 1 failure |
| b14 | HFO pump 2 failure |
| b15 | HFO fuel pipes failure |
| b16 | boiler failure |
| b17 | steam pipe connector failure |
| b18 | damaged steam pipe |
| b19 | K1 induced draft fan failure |
| b20 | K1 motor bearings failure |
| b21 | K1 motor rotor failure |
| b22 | K1 motor stator failure |
| b23 | loss of power supply |
| b24 | coupling failure |
| b25 | main drive gearbox filter blockage |
| b26 | main drive gearbox oil pump failure |
| b27 | main drive gearbox hose failure |
| b28 | main drive gearbox radiator failure |
| b29 | main drive gearbox oil cooler leakage |
| b30 | main drive gearbox oil filtration failure |
| b31 | main drive gearbox oil particle contamination |
| b32 | main drive gearbox oil poor viscosity |
| b33 | girth/pinion gearbox filter blockage |
| b34 | girth/pinion gearbox oil pump failure |
| b35 | girth/pinion gearbox hose failure |
| b36 | girth/pinion gearbox radiator failure |
| b37 | girth/pinion gearbox oil cooler leakage |
| b38 | girth/pinion gearbox oil filtration failure |
| b39 | girth/pinion gearbox oil particle contamination |
| b40 | girth/pinion gearbox oil poor viscosity |
| c1 | blending compressor failure |
| c2 | blending silo canvas damaged |
| c3 | blending silo extraction air slide blockage |
| c4 | limestone weigh-belt load cells failure |
| c5 | torn limestone weigh-belt |
| c6 | limestone weigh-belt tracking roller failure |
| c7 | limestone weigh-belt tension bolt failure |
| c8 | limestone weigh-belt tail drum pads failure |
| c9 | limestone weigh-belt head drum pads failure |
| c10 | iron ore weigh-belt load cells failure |
| c11 | torn iron ore weigh-belt |
| c12 | iron ore weigh-belt tracking roller failure |
| c13 | iron ore weigh-belt tension bolt failure |
| c14 | iron ore weigh-belt tail drum pads failure |
| c15 | iron ore weigh-belt head drum pads failure |

| | |
|---|---|
| c16 | sand weigh-belt load cells failure |
| c17 | torn sand ore weigh-belt |
| c18 | sand weigh-belt tracking roller failure |
| c19 | sand weigh-belt tension bolt failure |
| c20 | sand weigh-belt tail drum pads failure |
| c21 | sand weigh-belt head drum pads failure |
| c22 | alumina weigh-belt load cells failure |
| c23 | torn alumina ore weigh-belt |
| c24 | alumina weigh-belt tracking roller failure |
| c25 | alumina weigh-belt tension bolt failure |
| c26 | alumina weigh-belt tail drum pads failure |
| c27 | alumina weigh-belt head drum pads failure |

## Appendix 2. Intermediate events

| | |
|---|---|
| IA1 | burner misalignment |
| IA2 | high K1 vibration |
| IA3 | induced fan damper fails closed |
| IA4 | worn/cracked K1 tyre and support rollers |
| IA5 | damper arm stiff due to lack of lubricant |
| IA6 | inadequate power cylinder operating pressures |
| IA7 | overheating of K1 tyre and support rollers |
| IA8 | caked grease |
| IA9 | grease is molten |
| IA10 | poor lubrication (graphite blocks) |
| IA11 | ingress of dust |
| IA12 | insufficient graphite |
| IA13 | poor quality of graphite |
| IA14 | inadequate graphite-to-K1 tyre contact |
| IA15 | particle contamination |
| IB1 | thermal shock |
| IB2 | K1 disturbance |
| IB3 | rapid heating |
| IB4 | rapid cooling |
| IB5 | feed loss |
| IB6 | fuel loss |
| IB7 | loss of draft |
| IB8 | inadequate K1 speed |
| IB9 | storage silo extraction difficulty |
| IB10 | lignite fuel loss |
| IB11 | HFO fuel loss |
| IB12 | K1 electric motor |
| IB13 | lack of extraction air |
| IB14 | HFO pumps |
| IB15 | loss of steam temperature |
| IB16 | steam leakage |
| IB17 | K1 gearbox |
| IB18 | main drive gearbox |
| IB19 | girth/pinion gearbox |
| IB20 | crack/wear/broken main drive gears |

| | |
|---|---|
| IB21 | crack/wear/broken girth/pinion drive gears |
| IB22 | main drive gearbox overheating |
| IB23 | girth/pinion drive gearbox overheating |
| IB24 | poor lubrication of main drive gearbox |
| IB25 | poor lubrication of girth/pinion drive gearbox |
| IB26 | lubrication oil shortage (main drive gearbox) |
| IB27 | oil cooler failure (main drive gearbox) |
| IB28 | poor oil quality (main drive gearbox) |
| IB29 | lubrication oil shortage (girth/pinion drive gearbox) |
| IB30 | oil cooler failure (girth/pinion drive gearbox) |
| IB31 | poor oil quality (girth/pinion drive gearbox) |
| IC1 | poor raw material quality |
| IC2 | poor K1 design/manufacturing quality |
| IC3 | non-homogenous K1 feed |
| IC4 | inadequate blending |
| IC5 | raw materials weighing system malfunction |
| IC6 | limestone weighing system malfunction |
| IC7 | iron ore weighing system malfunction |
| IC8 | sand weighing system malfunction |
| IC9 | alumina weighing system malfunction |
| IC10 | misaligned limestone weigh-belt |
| IC11 | misaligned iron ore weigh-belt |
| IC12 | misaligned sand weigh-belt |
| IC13 | misaligned alumina weigh-belt |

## Appendix 3. Undeveloped events

| | |
|---|---|
| UA1 | programmable logic controller failure |
| UA2 | K1 tyre and support rollers misalignment |
| UA3 | poor quality of tyre and support rollers |
| UA4 | poor graphite manufacturing process |
| UB1 | poor air-to-fuel ratio |
| UB2 | K1 motor winding |
| UB3 | main drive gearbox bearing failure |
| UB4 | excessive main drive gearbox vibration |
| UB5 | girth/pinion drive gearbox bearing failure |
| UB6 | excessive girth/pinion drive gearbox vibration |
| UB7 | poor quality of main drive gearbox gears |
| UB8 | poor quality of girth/pinion drive gearbox gears |
| UB9 | main drive gearbox cooling system failure |
| UB10 | girth/pinion drive gearbox cooling system failure |
| UC1 | K1 concentricity/ovality |
| UC2 | K1 axial run-out |