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Monitoring Safety of Process Operations Using Industrial Workflows

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Abstract: An industrial workflow represents a sequence of tasks or actions that describes an operational procedure. In this paper, workflow strategies are developed that capture operational knowledge by analyzing event logs of how an operator has executed a procedure while controlling or monitoring a process. In this work, our prime focus is on infrequent process operations such as plant start-up and shutdown procedures. We propose a workflow conformance method to continuously monitor and compare operator actions with standard operating procedures (SOPs) and identify procedural violations that could compromise process safety and efficiency. An industrial case study is presented to illustrate applications of workflow conformance monitoring to identify operational problems associated with human factors, process and instrumentation.

Keywords: Standard operating procedures, Process safety, Workflows, Event logs, Workflow mining, Conformance monitoring, Process monitoring.

1. INTRODUCTION

In today's competitive global market, some of the key operational constraints confronting the process industry are shortage of skilled workforce and procedural violations during normal, plant start-up and shutdown operations which result in process upsets, thereby negatively impacting process performance. Operational inconsistencies during grade transitions introduce variability that affects product quality and financial performance of a company.

Based on 18 plant studies in the U.S, Canada, and Europe, the Abnormal Situation Management (ASM) consortium has reported that 40% of abnormal situations in process operations are directly attributed to people and workplace settings as shown in Figure 1 (ASM Consortium, 2007). In the context of ASM Consortium research, an abnormal situation is considered an event that requires operator intervention (Bullemer, et al., 2011). According to a research study carried out by the ASM Consortium, the majority of operating procedure execution failures had occurred during abnormal situations (Bullemer, et al., 2011). Factors such as inadequate skills and experience levels of the operational crew, failures to make consistent response and procedural violations during infrequent process operations such as start-up and shutdown procedures pose serious threat to plant safety and profitability (Walker, et al., 2011).

The Center for Chemical Process Safety (CCPS) has recommended metrics for measuring process safety performance of an organization (CCPS, 2011). Procedural violations are categorized under unsafe operating behaviors

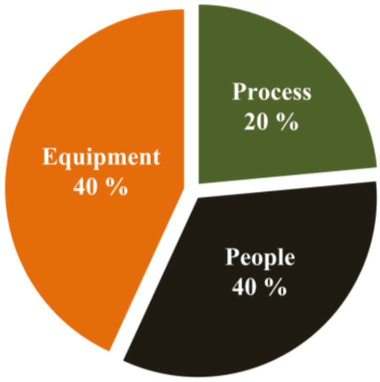

Fig. 1. Sources of abnormal events in process industry

that hurt process safety. CCPS metrics for measuring failure to follow procedures is defined as *"the percentage of the number of safety critical tasks observed where all steps of the relevant safe working procedure were not followed to the total number of safety critical tasks observed"* (CCPS, 2011).

Monitoring and identifying procedural deviations are critical tasks to ensure operational discipline, compliance and safety (Rains, 2010). The workflow framework developed in this paper is instrumental in identifying instances when a stipulated operating procedure is not followed. The concept of workflow conformance monitoring is demonstrated from an analysis of event logs to develop burner rotation workflows of boiler operations at the Heating plant of the University of Alberta. Workflows that do not conform to set procedures are further investigated to identify and troubleshoot operational problems.

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2. EVENT LOGS AND WORKFLOW MINING

2.1 Event Logs in Process Industry

With the availability of state-of-the-art information systems used in the process industry, the majority of the operator interactions with the plant floor (process and equipment) such as set-point changes, controller tuning steps, control loop diagnostic steps, and instrument troubleshooting tasks are archived in the event log database as shown in Figure 2.

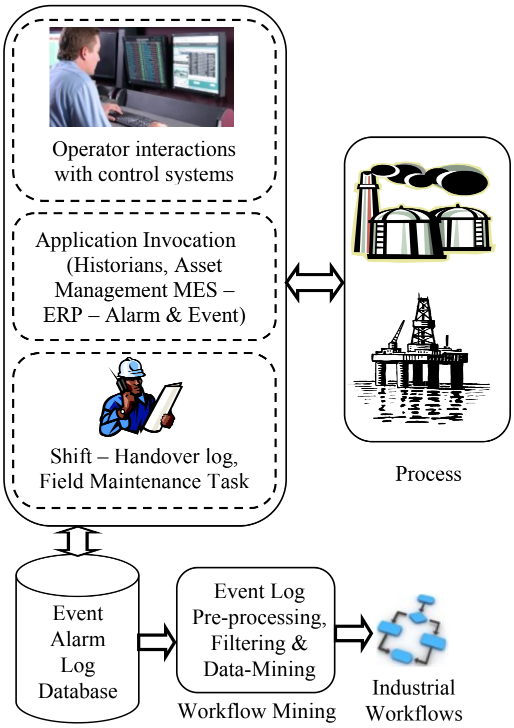

Fig. 2. Block Diagram for developing industrial workflows

Application invocations such as operators viewing process trends, historians, process alarms, requests for system diagnostic information and maintenance tasks are also archived in the event log database. Hence, an event log database is a rich source of process and operational knowledge. These archived text-based event messages are collected in the form of Excel spreadsheets and are pre-processed, filtered and data-mined to extract industrial workflows using workflow mining tools such as Disco software (Günther & Aalst, 2007). In our industrial case study, we extract workflows by analyzing event logs associated with the start-up procedure of Boiler #4 at the Heating plant on November 09, 2012. Start-up of Boiler #4 is a complex task and consists of 18 steps which span over 21 pages of a paper-based SOP. To simplify our analysis, we focus on developing workflows for a critical sub-process called burner rotation sequence. Section 4 provides a detailed explanation of event log pre-processing and filtering steps associated with the burner rotation.

2.2 Workflow Mining Tools

Workflow mining or process mining refers to the technique of capturing the best operating practices by analyzing text-based event logs associated with the execution of a process. Workflow mining techniques are widespread in the areas of business process management (Turner, et al., 2008). In this paper, we intend to use these techniques in the context of operations related to the process industry. For extracting workflows from archived event logs, we use a demo version of Disco, an automated process discovery software developed by Fluxicon, a spin-off of process mining research at Eindhoven University of Technology (TU/e) (Dongen, et al., 2005).

3. INDUSTRIAL CASE STUDY: BOILER OPERATIONS AT A HEATING PLANT

3.1 Description of the Process

The Heating plant at the University of Alberta supplies steam required for campus space heating and research facilities. The plant is a cogeneration facility that has a steam production capacity of 650 tonnes per hour and the steam load varies with season. The plant has two boilers which produce steam at 2,760 kPa and three boilers producing steam at 6,200 kPa. We focus on the start-up procedure of Boiler #4 which is a 6,200 kPa natural-gas fired boiler which runs continuously during the winter terms. A schematic of a natural-gas fired drum-type boiler is shown in Figure 3.

A drum-type boiler has two drums; namely a steam drum and a mud drum. These two drums are connected through a series of water-tubes called risers and downcomers. Steam is generated when these water-tubes are exposed to heat within the gas combustion furnace where a mixture of natural gas and air is ignited at a gas burner. Gas burners ensure proper mixing and combustion of natural gas and air in the boiler furnace. Steam and water rise up in the tubes that are closer to the furnace (risers) and water drops in the tubes which are farther away from the furnace (downcomers) creating a water circulation phenomenon (Heselton, 2005). Steam accumulated at the steam drum (top drum) flows through a series of tubes which are exposed to the furnace where any entrained water droplets in the steam are completely vaporized (resulting in dry steam). This part of the boiler section where the temperature of the steam is raised is called a superheater.

As shown in Figure 3, most industrial type boilers are equipped with multiple burners. Figure 4 shows the physical orientation of the six burners associated with Boiler #4 in the Heating plant. The warm-up rate of a boiler during a start-up is specified by the boiler manufacturer. Rapid warming up of a boiler during start-up results in temperature swings creating thermal stress on thick metallic tubes associated with boiler drums, superheaters, and economizers. Especially, superheater headers are subjected to slow warm up to prevent hand-hole welds from cracking. Hence, during a start-up, boilers are warmed up gradually by rotating burners. Based on the design specifications of Boiler #4, the rate of warm-up from a cold setting is limited to 38 deg C rise per hour (1500 kPa per hour) while rotating the burners.

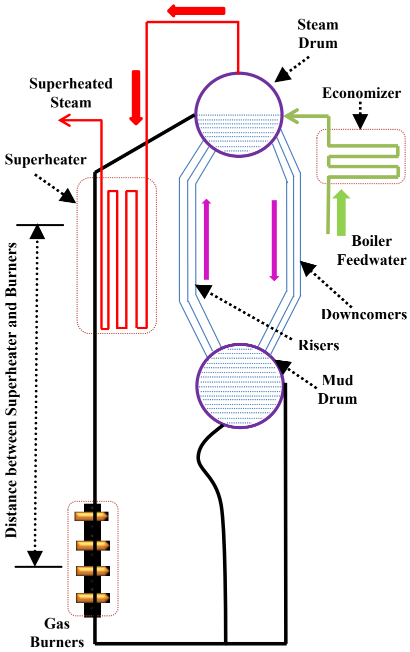

Fig. 3. Schematic of a drum-type natural-gas fired boiler

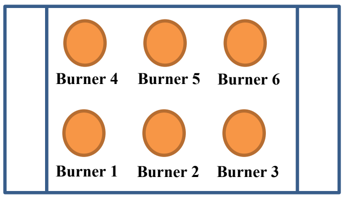

Fig. 4. Arrangement of burners in Boiler #4 at the Heating Plant, University of Alberta

3.2 *Recommended Practice for Burner Rotation Sequence*

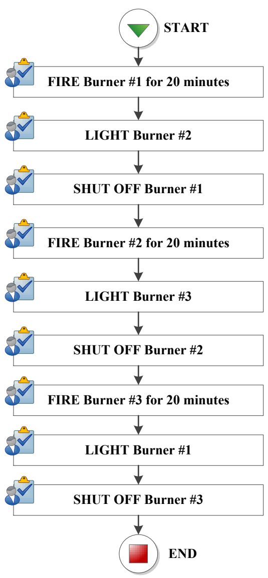

Fig. 5. Recommended burner ignition sequence for Boiler #4

Figure 5 shows a recommended practice obtained from the SOP for the burners ignition process during the start-up of Boiler #4. Notice that each burner is ignited for 20 minutes before switching to another burner. The subsequent burner is ignited before shutting down the current burner. This is done to avoid a purge of the burner section gases, which automatically occur in case of a flame failure. The number of burners ignited and rotated during a warm-up period depends on whether Boiler #4 is brought to operating conditions from a cold-setting or from a hot standby. During a boiler start-up, operators at the Heating plant always follow the burner rotation sequence as shown in Figure 5 to prevent uneven heating of superheater headers. As shown in Figure 4, it is inferred that the burners which are located in the bottom (#1, #2, and #3) are ignited first during the burner rotation sequence to ensure uniform heating of the boiler components.

4. PRE-PROCESSING EVENT LOG DATA FOR BURNER ROTATION SEQUENCE

Boiler #4 is controlled and monitored by a PROVOX control system that is interfaced to an OSIsoft PI Server from where event data is retrieved in the form of Excel files for analysis and report generation. We analyze alarm and event messages which are associated with the start-up of Boiler #4 on November 09, 2012. The campus heating load is generally at its peak at this time of the year and hence this boiler was started up from a hot standby condition. The boiler start-up procedure began at 02:00 PM and was brought to operating conditions by 05:00 PM on the same day. During this period of three hours, a total of 735 alarms and events were archived in the PROVOX system.

4.1 *Filtering Event Logs Corresponding to Boiler #4*

The raw event log spreadsheet was complex and contained about 225 Excel columns representing various data attributes related to Boiler #4 operations. Some of the data attributes such as system nodes, system configuration alerts, device address, alarm grouping, and alarm priorities were less relevant to workflow mining tasks. To develop workflows for burner rotation sequence, pre-processing is carried out on the raw event log spreadsheets by filtering events that are relevant to burner rotation sequence shown in Table 1.

Table 1. A section of filtered event messages corresponding to the burner rotation sequence

Event Date	Event Time	Area	Point Tag	Point Desc	SpStr	PvStr
11/09/2012	02:51:17 PM	BOILER-4	BB-4050	B4 Burn1 Sta	Off Line	On Line
11/09/2012	02:51:20 PM	BOILER-4	BB-4050	B4 Burn1 Sta	On Line	On Line
11/09/2012	02:51:22 PM	BOILER-4	BB-4050	B4 Burn1 Sta	On Line	On Line
11/09/2012	02:51:41 PM	BOILER-4	BB-4050	B4 Burn1 Sta	On Line	Off Line
11/09/2012	02:52:09 PM	BOILER-4	BB-4050	B4 Burn1 Sta	On Line	Off Line

Event log pre-processing also ensures that the event log file is compatible with Disco software, which can then be used to generate the burner rotation workflows automatically. From Table 1, columns “Event Date” and “Event Time” represent the actual date of occurrence and time stamps of the events respectively. Column “Area” denotes the unit or the piece of equipment under consideration which is Boiler #4 in our case. Columns “PointTag” and “PointDesc” describe the tag name of an instrument and its description respectively. Column “PvStr” represents the current status of an instrument where as “SpStr” denotes the set-point status of an instrument as set by the control room operator.

4.2 Creating Custom Event Messages

Although the PROVOX system archives all events associated with boiler operation, any single data attribute (each column in Table 1) alone does not convey meaningful information of the entire process by itself. It is, therefore, necessary to create unique text messages from the event logs, which will enable workflow mining tools to capture all critical tasks associated with the burner rotation sequence. Text character strings of each and every event associated with columns “PointTag”, “PointDesc” and “SpStr” or “PvStr” are concatenated to create unique *Custom_Event_Message* text-strings as shown in Tables 2 and 3.

Event messages archived under “SpStr” column take two states namely; ‘On Line’ or ‘Off Line’ which represents the set-point status of burners as set by the control room operator during boiler warm-up operation. Hence, each Custom_Event_Message string in Table 2 represents an operator action while rotating the burners.

Table 2. A section of custom event messages created based on operator set-point status of the burners

Time Stamp	Point Tag	Point Desc	Custom_Event_Message
02:51:17	BB-4050	B4 Burn1 Sta	BB-4050-B4 Burn1 Sta(Off Line)
02:51:20	BB-4050	B4 Burn1 Sta	BB-4050-B4 Burn1 Sta(On Line)
02:51:22	BB-4050	B4 Burn1 Sta	BB-4050-B4 Burn1 Sta(On Line)
02:51:41	BB-4050	B4 Burn1 Sta	BB-4050-B4 Burn1 Sta(On Line)
02:52:09	BB-4050	B4 Burn1 Sta	BB-4050-B4 Burn1 Sta(On Line)

Each custom event message string can be deciphered into three components for our analysis as shown in Figure 6.

$$\underbrace{\textbf{BB-4050-}}_{\text{Tag Name}}\underbrace{\textbf{B4 Burn1 Sta}}_{\text{Tag Description}}\underbrace{\textbf{(Off Line)}}_{\text{Set-point/ Current Status}}$$

Fig. 6. Interpreting a custom event message string

Table 3. A section of custom event messages created based on the current status of the burners

Time Stamp	Point Tag	Point Desc	Custom_Event_Message
02:51:17	BB-4050	B4 Burn1 Sta	BB-4050-B4 Burn1 Sta(On Line)
02:51:20	BB-4050	B4 Burn1 Sta	BB-4050-B4 Burn1 Sta(On Line)
02:51:22	BB-4050	B4 Burn1 Sta	BB-4050-B4 Burn1 Sta(On Line)
02:51:41	BB-4050	B4 Burn1 Sta	BB-4050-B4 Burn1 Sta(Off Line)
02:52:09	BB-4050	B4 Burn1 Sta	BB-4050-B4 Burn1 Sta(Off Line)

Similarly, event messages archived under “PvStr” column take two states namely; ‘On Line’ or ‘Off Line’ which represents the current status of burners during boiler warm-up operation. Each Custom_Event_Message string shown in Table 3 indicates whether a burner is currently ignited or shut off. There are 23 custom event messages associated with burner rotation during the start-up of Boiler #4 on November 09, 2012. Data pre-processing allows Disco to automatically extract workflows based on time stamps and custom event messages. Each custom event message string appears as a block in the workflows which are shown in Figures 7 and 8.

5. WORKFLOWS FOR BURNER ROTATION SEQUENCE

5.1 Based on Set-point Status Set by the Operator

The workflow shown in Figure 7 is extracted from custom event messages which are created based on set-point status of the burners (“SpStr”) as described in Table 2. A control room operator sets these states in the PROVOX control system when a burner is ignited or shut off during boiler warm-up. A burner rotation workflow developed based on the set-point status of the burners (Figure 7) captures operator actions (set-point changes in the operator console) during the burner rotation sequence. According to the workflow shown in Figure 7, Burner #1 is taken online (ignited) first and then switched to Burner #4 while shutting off (offline) Burner #1. After igniting Burner #4, ignition is switched to Burner #3 while Burner #4 is shut off. Finally Burner #2 is taken online (ignited). Warm-up of Boiler #4 continues with Burner #2 and Burner #3 ignited while the boiler reaches operating steam conditions. The frequency of occurrence of an operator action is shown with a number within each block. Similarly, a directed arrow connecting two blocks indicates the path of actions or events during the burner rotation sequence. A number on the directed arrow indicates the number of times a particular transition occurred between two blocks in the direction of the arrow.

5.2 Based on Current Status of the Burners

Figure 8 shows a burner rotation workflow extracted from custom event messages which are created based on the current status of the burners (PvStr) as described in Table 3.

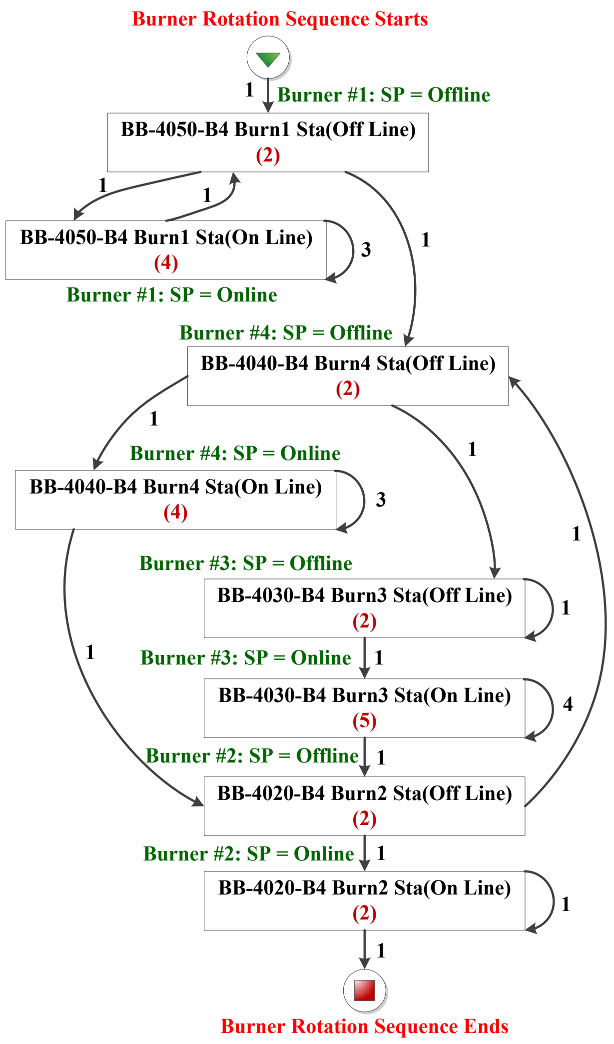

Fig. 7. Burner rotation workflow developed based on operator actions

We can infer from this workflow that Burner #1 is ignited first and then switched to Burner #4 while shutting off Burner #1. After igniting Burner #4, ignition is switched to Burner #3 while Burner #4 is shut off. Boiler #4 is brought to operating conditions by continuing ignition with Burner #2 and Burner #3. A burner rotation workflow developed based on the current status of the burners (Figure 8) captures on-going events or burner status during a boiler warm-up procedure. Such a workflow captures the status of the process (burners in our case) and provides an insight into the health and diagnostic information about the instrumentation as well.

6. WORKFLOW CONFORMANCE MONITORING

Very often a process deviates from its expected behavior for several reasons such as; changing operating conditions or constraints, operators failing to follow an established procedure, operational inconsistencies during start-up, shutdown and transitions, process and equipment failure to name a few. As event log database continuously archives events and alarms that are generated in the plant, process deviations are recognized in terms of alarms and non-conformance events that arise during an abnormal plant behavior.

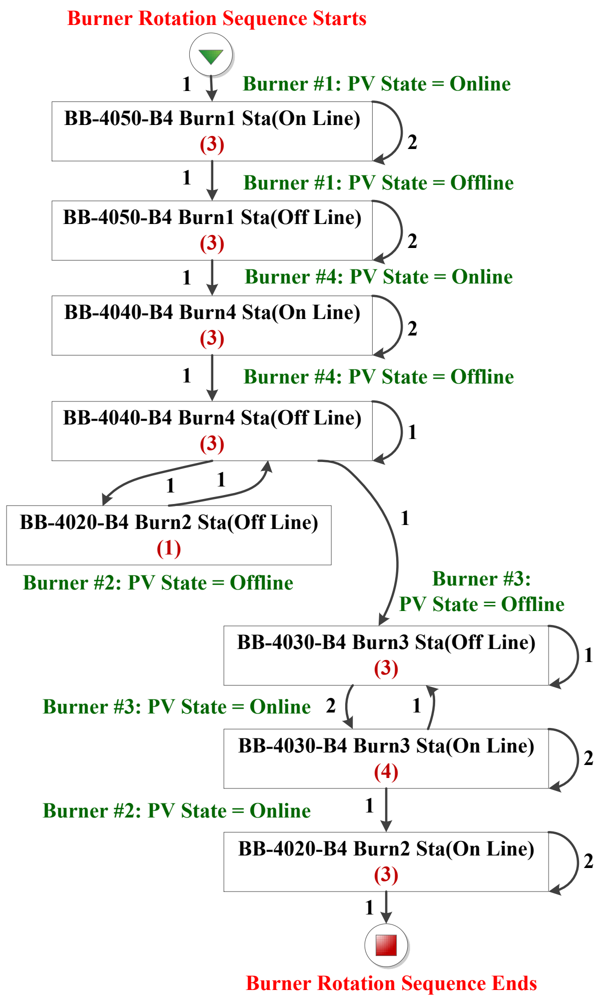

Fig. 8. Burner rotation workflow developed based on the current status of the burners

When a workflow is extracted from event logs, these abnormal alarms and non-conformance events appear as message blocks along with the anticipated events. Hence, process deviations are identified visually on-the-fly by comparing current workflows with stipulated operating procedures or best operating practices.

Conformance monitoring helps to continuously monitor operator actions and on-going events by comparing them with an existing workflow model or SOP or a 'best-practice' operational guideline. Hence, conformance monitoring helps to identify operators who deviate from an established procedure. Deviations observed in the workflow activities are further investigated to understand and solve operational problems associated with process, equipment and human factors. Based on the workflows (Figures 7 and 8) developed for burner rotation sequence of Boiler #4, we arrived at 4 key findings which are summarized in the following subsections. These outcomes were further validated by discussions with the shift operational crew who had brought Boiler #4 online from a hot standby on November 09, 2012.

6.1 Finding #1 – Mismatch of Burner Tag Names

The tag name of Burner #1 should be BB-4010. However, based on burner rotation workflows shown in Figures 7 and 8, it is visually evident that the tag name of Burner #1 is incorrectly identified as BB-4050. Actually, the tag name BB-4050 corresponds to Burner #5 which was not ignited during the start-up of Boiler #4 on November 09, 2012. This discrepancy in burner tag names has been reported to plant personnel for further investigation. Mismatched tag names result in archiving faulty information about an instrument in process trends or historians and can cause confusion when responding to alarms in an emergency situation.

6.2 Finding #2- Procedural Deviations

According to the SOP for burner rotation sequence shown in Figure 5, when Boiler #4 is warmed up from a cold setting, burners are rotated such that Burner #1 is ignited first for 20 minutes; then Burner #2 is ignited for 20 minutes while Burner #1 is shut off, and then Burner #3 is ignited for 20 minutes. However, the ignition sequence captured in workflows which are extracted from the actual events (Figures 7 and 8) deviate from this recommended practice. Based on the information from shift supervisor's log stored on November 09, 2012, it was found that Boiler #4 is brought online from a hot standby, and hence any of the two bottom burners can be ignited without rotating the burners. This fact clears up the reason behind the observed procedural deviation. However, it is apparent the SOP should be revised to reflect this practice.

6.3 Finding #3- Issues with Sensitivity of Flame Scanner

Burner #4 is physically situated on top of Burner #1 in Boiler #4 as shown in Figure 4. Burner #4 appears in burner rotation workflows captured from the actual events. However, the shift supervisor's log indicates that Burner #4 was not ignited during start-up on November 09, 2012. On further investigation, it was found that the sensitivity of flame scanner is too high such that it is picking a signal from Burner #1 and is misinterpreted as a flame at Burner #4.

6.4 Finding #4- Operator Actions Versus On-going Events

By comparing the workflows shown in Figures 7 and 8, it is possible to monitor whether the field instruments are actually responding in a way they are set by the operator in the control room. Non-conformance message blocks observed in workflows developed from operator set-points and on-going events point towards a possible requirement for preventive maintenance of the field devices. In our case study, the sequences of burner ignition in both workflows match.

6.5 Auditing of Operating Procedures

Gruhn et al. (2006) stated that in order for operating procedures to be accounted for as a protection layer for process safety, procedures are required to be documented; plant personnel are trained to follow them and their implementation must be audited. This statement emphasizes the importance of conformance monitoring of operator actions with respect to process safety. Conformance monitoring provides documented information (audit) on operator actions while executing a procedure in order to meet regulatory compliance. By comparing Figures 5 and 7, one can check if the sequence of operations for burner rotation were followed correctly as per the SOP guidelines.

7. CONCLUSIONS

One of the key visual aspects of the proposed workflow framework is that event messages corresponding to operator actions or on-going events appear as text-based message blocks or activities in the workflow diagram. Hence, procedural violations, through audits, are identified in real time or on-the-fly to ensure process safety and procedural compliance. The benefits of workflow conformance in identifying operational problems are demonstrated using an industrial case study. Further, workflows extracted from the event logs of an expert operator capture valuable operational knowledge which can then be used to train a new generation of operational crew. Hence, the proposed workflow framework can significantly benefit the process industry by providing tools to improve operator skills, achieve superior operational visibility and enforce operational discipline.

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