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AUTOMATED CAUSE & EFFECT ANALYSIS FOR PROCESS PLANTS

H. An*, P.W.H.Chung*, J McDonald**, J. Madden**

*Department of Computer Science, Loughborough University, Loughborough, UK,
**Hazid Technologies Ltd, Beeston Business Park, Beeston, Nottingham, UK

Cause & Effect (C&E) analysis for process plants is one of the tasks associated with Process Control Engineering (PCE). With the availability of electronic Piping and Instrumentation Diagrams (P&IDs), a Computer-Aided system is developed to carry out the analysis automatically by encoding knowledge related to PCE in rules so that they can be applied to a given set of P&IDs to produce the corresponding C&E Diagrams. This paper describes how this is achieved. A rule-based system and an instrument checker are developed. They are used to generate the results and the results are displayed in a format that complies with ISO 10418 (ISO, 2003).

1. INTRODUCTION

Safety analysis in control design of a process plant is required to help with the identification of unfavourable outcomes that may present a safety risk and to help with the design of protective measures to avoid or to mitigate against such unfavourable events. (International Organization for Standardization (ISO), 2003).

Safety Analysis Function Evaluation chart (SAFE) is one of the established cause-effect analysis techniques stated in the ISO standard 10418 (ISO, 2003). It can be applied to achieve the above objectives and ensure that the procedures and devices provided for safeguarding the process components form an integrated system covering the entire process plant. The SAFE chart is referred to as Cause & Effect (C&E) table as it provides information about process events and process responses.

Manual generation of a C&E table given a P&ID of a process plant is labour intensive, time consuming and error-prone. With P&IDs available in electronic format there is the potential of developing a computer-aided tool that can take the P&ID information as input and produce the C&E analysis result automatically.

Several computer-aided tools of this kind have been developed, such as a knowledge-based system described in R. Drath et al., (2006) that illustrates the auto-generation of C&E table through a standardized plant description model called **C**omputer **A**ided **E**ngineering e**X**change (CAEX) and rule-based algorithms. It uses the specification and implementation of interlocks as an example. There are other commercial tools that provide an easy way of filling in the C&E table, although they are not knowledge-based tools.

This paper introduces a novel C&E system that has been developed recently as a joint project between Hazid Technologies Ltd. and Loughborough University, UK. The system is integrated with HAZID system (Hazid Technology. Ltd., 2008). HAZID is a knowledge-based system which automates the process of HAZard and OPerability Study (HAZOP) by taking information from the P&IDs as input. The purpose of the C&E System is to automate the generation of C&E tables from the same P&ID input information. This reduces the labour intensive analysis effort required of the control engineers.

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This paper highlights the novelty of the C&E system and describes its components and the reasoning process. Two examples are used to illustrate the working of the system. The first is a small part of a P&ID of a larger plant just to illustrate the working of the system. The second is the interlock system described in R. Drath et al., (2006). The system and results described by R.Drath et al., (2006) are compared with the current system. The paper ends with a summary of the overall methodology.

2. COMPONENTS OF THE C&E SYSTEM

The C&E system consists of an Instrument Checker, a general purpose knowledge-based rule engine and an output tool that generates the C&E table that can be easily displayed in Microsoft Excel. Output from the Instrument Checker is converted into input of the rule engine. Output from the rule engine is converted into a format that automatically generate the C&E table in a format complied with 10418 (ISO 2003).

The working flow of the overall C&E system is shown in figure 1.

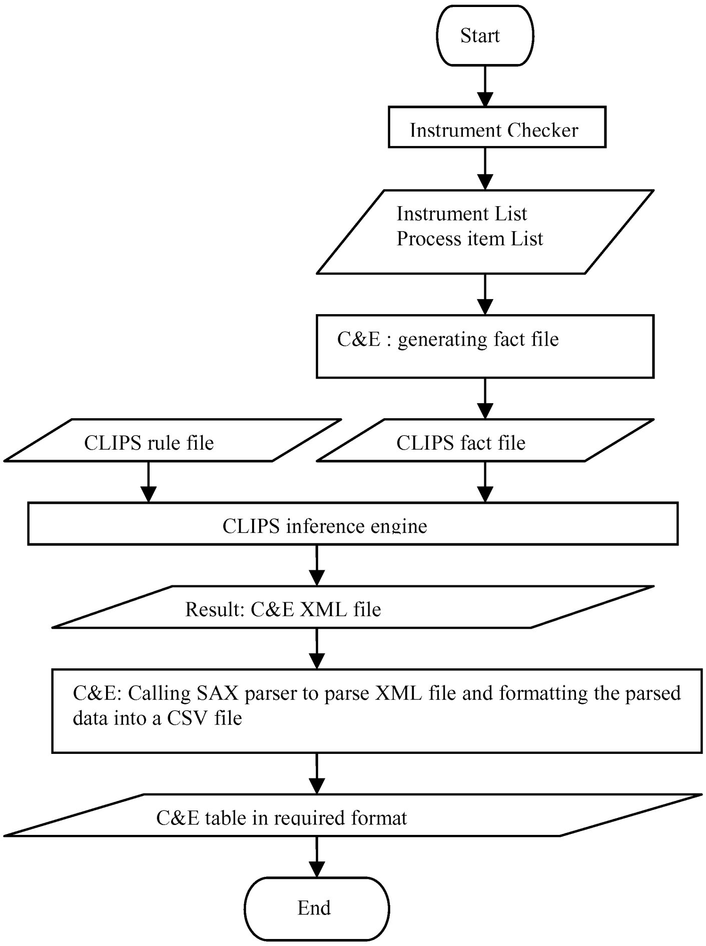

Figure 1. Work flow for Cause & Effect Analysis

3. INSTRUMENT CHECKER

Given a P&ID, the Instrument Checker identifies the instrument loops and their connections with the process items. The result of this tool is used as input by both HAZID and the C&E system. The tool first identifies all the instruments in the process plant. For each instrument, it then traces the upstream and downstream connections of each branch line until a process item is found. Therefore, information about which process items are connected to which instruments is collected. Therefore, given a process item the Instrument Checker can list which instruments are connected to it, and can also list which process items are connected to a given instrument.
Consider the P&ID shown in figure 2, which is a small part taken from a large plant. The tool identifies the following instruments:

Two high level alarms – "ZEH-59010" and "ZLH-59010";
Two low level alarms – "ZEL-59010" and "ZLL-59010";
One control valve – "FCV-59010".

The tool then traces upstream and downstream to find the process item(s) attached to these instruments. In this case they are all connected to the same pipe with the tag "test1001PU34-PU".

Figure 3 shows the results. The loop number "59010" indicates that they are all in the same instrument loop. It also shows the related deviations of each instrument ("L+" means "high level", "L-"means "low level", "L0" means "no level") and the response, which can be either an indicator, an alarm or a control.

Figure 4 shows all the instruments ("ZEH-59010", "ZLH-59010", "ZEL-59010", "ZLL-59010" and "FCV-59010") that are attached to the same process item ("test1001PU34-PU").

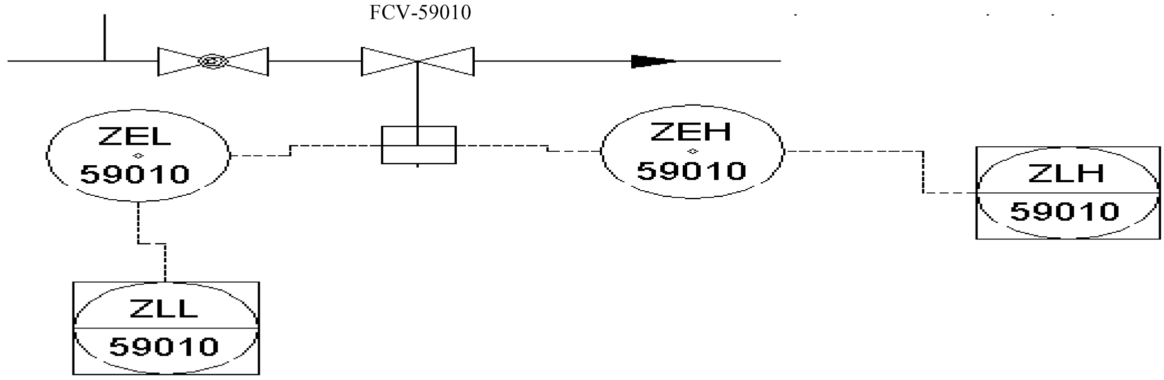

Figure 2. A simple instrument loop

Instrument List

Loop	Item Tag	Item Type	Associated Deviation	Process Item	Response
59010	ZEH-59010	high level alarm	L+ , L0	test1001PU34-PU_24 , test1001PU34-PU_29	isIndicator , isAlarm
59010	ZLH-59010	high level alarm	L+ , L0	test1001PU34-PU_24 , test1001PU34-PU_29	isIndicator , isAlarm
59010	ZEL-59010	low level alarm	L- , L0	test1001PU34-PU_24 , test1001PU34-PU_29	isAlarm
59010	ZLL-59010	low level alarm	L- , L0	test1001PU34-PU_24 , test1001PU34-PU_29	isAlarm
59010	FCV-59010	cv body		test1001PU34-PU_24 , test1001PU34-PU_29	isControl

Figure 3. Instrument List

Process Item List   Highlight in SP

Process Item Tag	Process Item Type	Instrument Tag	Instrument Name	Associated Deviation	Response
test1001PU34-PU_24	Primary Piping	ZEH-59010	high level alarm	L+ , L0	isIndicator , isAlarm
test1001PU34-PU_24	Primary Piping	ZLH-59010	high level alarm	L+ , L0	isIndicator , isAlarm
test1001PU34-PU_24	Primary Piping	ZEL-59010	low level alarm	L- , L0	isAlarm
test1001PU34-PU_24	Primary Piping	ZLL-59010	low level alarm	L- , L0	isAlarm
test1001PU34-PU_24	Primary Piping	FCV-59010	cv body		isControl

Figure 4. Process Item List

4. ENCODING KNOWLEDGE RELATED TO PCE IN RULES AND MAKING USE OF CLIPS ENGINE

In order to analyze the process events and the corresponding process responses, a rule-based system is built for this purpose. The rule-base captures the expert's knowledge and carries out the inference to produce the result. CLIPS (C Language Integrated Production System) is chosen as the development tool as it supports rule-based, object-oriented and procedure programming methods (J.Giarratano & G.Riley 1994; G.Riley, 2008).

A rule-based system in CLIPS consists of three basic components: a set of facts, a set of rules and the inference engine that controls the overall execution by matching the rules against the facts to infer new information (J.Giarratano & G.Riley, 1994). Therefore, the first step for building our expert system is to generate the CLIPS fact file.

4.1 Converting the input into CLIPS fact file

Bearing in mind that the output of the Instrument Checker has already prepared all the necessary process item data and their connections with the instruments. Therefore the next step is to convert the file into the required format for the reasoning system as CLIPS facts.

The structure of each fact is:

```
([type],[tag],[item name]);[comment]
```

All the process items are classified as "equipment", eg.

```
(equipment pipe test1001PU34-PU 1-in-2-out); 1 in 2 out
```

This means equipment "test1001PU34-PU" is a "1-in-2-out" pipe.

All the instruments are classified according to its item name, eg.

```
(device high-level-alarm ZEH-59010);high level alarm
(device high-level-alarm ZLH-59010);high level alarm
(device low-level-alarm ZEL-59010);low level alarm
(device low-level-alarm ZLL-59010);low level alarm
(device cv-actuator NOTAG_Instrument_0_0.106_0.505);cv actuator
```

All the control instruments are classified as "equipment controlDevice", eg

```
(equipment controlDevice FCV-59010 cv-body);cv body
```

For all the pipes, the CLIPS fact file defines the "flow-connection", eg.

```
(flow-connection test1001PU34-PU out test1001PU34-P_4)
(flow-connection test1001PU34-P_4 out NOTAG_PipingComp_0_0.222_0.469)
(flow-connection NOTAG_PipingComp_0_0.222_0.469 out test1001PU34-P_2)
(flow-connection test1001PU34-P_2 out NOTAG_PipingComp_0_0.214_0.469)
```

The above flow-connection definitions indicate how pipe "test1001PU34-PU" is connected to other pipes and equipment items to deliver the flows.

If there is a flow connection from A to B, and there is a flow connection from B to C, then the CLIPS asserts an "in-line" fact as following:

"(in-line A to C)" indicates that there is a flow connection from A to C.

For all the signal lines, the CLIPS file defines the "signal-connection" facts as shown below.

```
(signal-connection ZLH-59010      NOTAG_SignalRun_33)
(signal-connection NOTAG_SignalRun_33      ZEH-59010)
(signal-connection ZEH-59010      NOTAG_SignalRun_39)
(signal-connection NOTAG_SignalRun_39      NOTAG_Instrument_0_0.106_0.505)

(signal-connection ZLL-59010      NOTAG_SignalRun_24)
(signal-connection NOTAG_SignalRun_24      ZEL-59010)
(signal-connection ZEL-59010      NOTAG_SignalRun_43)
(signal-connection NOTAG_SignalRun_43      NOTAG_Instrument_0_0.106_0.505)

(signal-connection NOTAG_Instrument_0_0.106_0.505      FCV-59010)
```

The above signal-connection facts show that "ZEH-59010", "ZLH-59010", "ZEL-59010", "ZLL-59010" and "FCV-59010" are connected by signals through a cv actuator "NOTAG_Instrument_0_0.106_0.505".

4.2 Developing the reasoning rules

The reasoning rules are defined according to ISO 10418 (2003). The principle of defining a rule is to make sure that it is as generic and reusable as possible.

Here is an example of a descriptive rule from the standard:

IF there is a level sensor;
AND there is a level vessel and it has (at least) one input;
AND there is (at least) a control valve that is able to close the input of the level vessel;
AND the level sensor can detect the level in the level vessel and raise an alarm;
THEN close the control valve(s) if   the level sensor raises a maximum alarm.

The equivalent rule in CLIPS format is:

```
(defrule levelVessel-highLevel-close-inputValve
    (device level-indicator | high-level-alarm ?HLA)
    (equipment pipe | majorProcessItem   ?VESSEL-TAG ?VESSEL-NAME)
    (equipment_controlDevic | controlDevicePump ?INPUT-CONTROL-DEVICE-TAG ?INPUT-CONTROL-DEVICE-NAME)
    (or(signal-connection ?HLA ?VESSEL-TAG)
        (signal-connection ?HLA ?INPUT-CONTROL-DEVICE-TAG))
    (in-line ?INPUT-CONTROL-DEVICE-TAG to ?VESSEL-TAG)
=>
(print-result-levelAlarmHigh     ?VESSEL-TAG     ?VESSEL-NAME     ?HLA     ?INPUT-CONTROL-DEVICE-TAG
?INPUT-CONTROL-DEVICE-NAME)
)
```

The above rule in CLIPS means:

The name of the rule is "levelVessel-highLevel-close-inputValve ";

IF
there is a level indicator or a high level alarm
AND
there is a vessel
AND
there is a control device which is either a control valve or a control pump
AND
the control device is connected to the vessel
AND
there is a signal connection between the level indicator or alarm to the control device or the vessel
THEN
conclude that the control device will be triggered when the level of the vessel reaches a high level.

4.3 The reasoning process

A rule is activated when all the conditions specified are satisfied by the facts contained in the system. When a rule is fired the action(s) specified will be taken. Normally the action is to call a function to write some output in the result file in XML format.

Consider the simple instrument loop shown in figure 2. It has a primary pipe "test1001PU34-PU", a high level alarm "ZEH-59010", and a control valve "FCV-59010". There is signal connection between the high level alarm and the control valve. There is a rule which asserts "(signal-connection ZEL-59010 FCV-59010)"since there are signal connection facts as given below:

```
(signal-connection ZEL-59010     NOTAG_SignalRun_43)
(signal-connection NOTAG_SignalRun_43     NOTAG_Instrument_0_0.106_0.505)
(signal-connection NOTAG_Instrument_0_0.106_0.505     FCV-59010)
```

There is also a flow connection from the control valve to the pipe "(flow-connection FCV-59010 out test1001PU34-PU)" to indicate this is an input control device.

Therefore, the rule “levelVessel-highLevel-close-inputValve” is activated as all the patterns at the left hand side of that rule are matched by the facts. The results are written into the result file in the XML format as shown below:

<cause_effect>
<cause_comment processItemTag='test1001PU34-PU'>Primary-Piping high level
</cause_comment>
<cause instrumentTag='ZEH-59010'>level alarm high</cause>
<effect controlInstrumentTag='FCV-59010'>close input control device: cv-body
</effect>
</cause_effect>

5. GENERATING THE EXCEL C&E RESULT TABLE

After the CLIPS tool generates the results in the XML format, a simple API for XML (SAX) Parser is called to parse the result and convert it into a Comma-Separated Values (CSV) text file. Once the CSV text file is generated, the engineer can open it with Excel, and the C&E result will be presented in the format specified in ISO 10418 (2003).
Part of the C&E table in Excel is shown in figure 5. The result shows that process component “test1001PU34-PU” has four instrument devices attached to it (“ZEH-59010”, “ZLH-59010”, “ZEL-59010”, “ZLL-59010”). If the high level alarm “ZEH-59010” or “ZLH-59010”goes off then the input control valve FCV-59010 will be closed. If the low level alarm “ZEL-59010” or “ZLL-59010” goes off then the input control valve FCV-59010 will be opened. The interconnecting cross marks are placed in the cells indicating the cause-effect link between the process component, sensor instrument and control device. The “Function Performed” column describes the action that will be taken on the control device.

	A	B	C	D	E	F	G	H	I	J	K
1	FIGURE SAFETY ANALYSIS FUNCTION EVALUATION CHART (SAFE)										
2						SHUTDOWN OIFUNCTION PERFORMED	open input control device:cv-body	close input control device:cv-body	open input control device:cv-body	open input control device:cv-body	
3							FCV-59010	FCV-59010	PCV-51001	XCV-51004	
4	PROCESS COMPONENT										
5	IDENTIFICATION	SERVICE	DEVICE IDENT	CAUSE COMMENT	CAUSE						
6	test1001PU34-PU	Primary Piping	ZEH-59010	Primary-Piping high level	level alarm high			X			
7			ZLH-59010	Primary-Piping high level	level alarm high			X			
8			ZEL-59010	Primary-Piping low level	level alarm low		X				
9			ZLL-59010	Primary-Piping low level	level alarm low		X				
10											

Figure 5. Part of the Cause & Effect Table in Excel

6. COMPARISON OF SYSTEMS

The knowledge-based Cause & Effect analysis system reported in R.Drath et al., (2006) provides an interlock example to illustrate its working. “Interlocks are pieces of control code that ensure the safety of a plant” (R.Drath et al., 2006). In order to do the comparison a similar P&ID as shown in figure 6 is tested using the system reported in this paper.

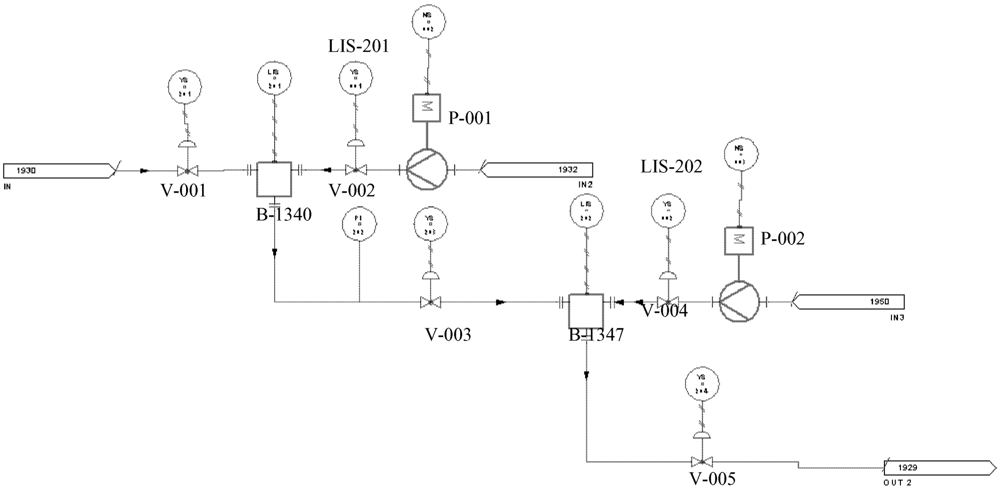

Figure 6. P&ID example extended from Drath et al., (2006)

In the P&ID, “B-1340” and “B-1347” are two blanketed fixed roof vessels; “V-001” and “V-002” are two input control valves for “B-1340”; “V-003” is an output control valve for “B-1340” and an input control valve for “B-1347”; “V-004” is an input control valve for “B-1347”; “V-005” is an output control valve of “B-1347”. “LIS-201” and “LIS-202” are the level sensors for “B-1340” and “B-1347” respectively.

The rules in the system are:

Rule 1: if the level in the vessel had reached to the maximum level then close the input device;
Rule 2: if the level in the vessel had reached to the minimum level then close the output device;
Rule 3: if the valve is closed then stop the in-line control pump to protect the pump;
Rule 4: if the pump is started then ensure the in-line valve is opened to protect the pump;
Rule 5: if there is error with the level sensor then close the input or output control valve/pump.

The results are shown in figure 7.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
1	FIGURE SAFETY ANALYSIS FUNCTION EVALUATION CHART (SAFE)																								
2						**SHUTI FUNCTION PERFORMED**	stop/close input control device :Generic-Centrifugal-pump	stop/close input control device :cv-body	stop/close input control device :cv-body	stop/close output control device: cv-body	stop/close input control device :cv-body	stop/close input control device :Generic-Centrifugal-pump	stop/close input control device :cv-body	stop/close output control device: cv-body	stop in-line control pump: Generic-Centrifugal-pump	open in-line control device:cv-body	stop in-line control pump: Generic-Centrifugal-pump	open in-line control device:cv-body	close input/ouput control device:cv-body	close input/ouput control device:cv-body	close input/ouput control device:cv-body	close input/ouput control device:Generic-Centrifugal-pump	close input/ouput control device:cv-body	close input/ouput control device:Generic-Centrifugal-pump	close input/ouput control device:cv-body
3							P-002	V-004	V-003	V-005	V-001	P-001	V-002	V-003	P-002	V-004	P-001	V-002	V-003	V-005	V-004	P-002	V-001	P-001	V-002
4	**PROCESS COMPONENT**																								
5	**IDENTIFI**	**SERVICE**	**DEVICE IDENT**	**CAUSE COMMENT**	**CAUSE**																				
6	B-1340	Blanketed Fixed Roof	LIS-201	Blanketed-Fixed-Roof	level alarm high						X	X	X												
7				Blanketed-Fixed-Roof	level alarm low									X											
8				Blanketed-Fixed-Roof	level-indicator error														X				X	X	X
9	B-1347	Blanketed Fixed Roof	LIS-202	Blanketed-Fixed-Roof	level alarm high		X	X	X																
10				Blanketed-Fixed-Roof	level alarm low					X															
11				Blanketed-Fixed-Roof	level-indicator error														X	X	X	X			
12	P-001	Generic Centrifugal pump	LIS-201																						
13		not attached to this proces	V-002	protecting pump:Gene	cv-body closed												X								
14		not attached to this proces	P-001	protecting pump:Gene	Generic-Centrifugal-pump started													X							
15	P-002	Generic Centrifugal pump	LIS-202																						
16		not attached to this proces	V-004	protecting pump:Gene	cv-body closed										X										
17		not attached to this proces	P-002	protecting pump:Gene	Generic-Centrifugal-pump started											X									

WholeResult | CauseEffectOnly

Figure 7 Cause & Effect Table in Excel for P&ID example extended from Drath et al (2006).

Comparing with the results produced in R. Drath et al., (2006), our C&E analysis has these unique features:

- The result table provides a comprehensive list of process components and their attached devices. The user also has the option of viewing only components that have cause-effect links that apply to them.
- The table provides more detailed classification of function performed. For example, "V-003" is an output control valve for "B-1340" and an input control valve for "B-1347". When there is a cause-effect control taken by "V-003", the "function performed" column will specify whether it acted as an input or output valve and put them in different column.

7. FURTHER DEVELOPMENT

There is a lot of potential to expand the reasoning rules. For example to incorporate configuration rules to check that the P&ID has all the necessary safe guards.

8. CONCLUSION

Carrying out safety analysis is important to prevent adverse consequence from occurring and to be of assistance to the control design of protective methods in a process plant. Control and sensor devices and their working procedures can be presented in a SAFE chart (or Cause & Effect (C&E) table) to help with the analysis process.
With the electronically available P&IDs, computer-aided tools can be developed to facilitate the labour-intensive analysis process.
A newly developed cause-effect analysis system is introduced in this paper to detail its components, working principles and data processing methods. Two examples are used to illustrate the working of the system. The highlights of the current system are that it provides a comprehensive list of process components and their attached devices that covers all the plant no matter whether there is a cause-effect applied to it or not and it offers two option in the result presentation as the user can choose to show only the cause-effect link as well as the complete set of results.

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