SHORT NOTE
Algorithm for Cause Analysis Using Cause Consequence Model

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It has been required to develop an operator aid system that informs, at plant disturbances, the primary causps and corrective counter operations in an on-line manner. For this purpose, several methods\(^{(1)(2)}\) for analyzing the primary causes have been studied utilizing the linearized plant dynamics model. But because of the non-linear characteristics of the plant and the long computation time, these methods have not always been effective.

Therefore, a more practical method using Disturbance Analysis Systems\(^{(3)(4)}\) has recently been studied. In these systems, Cause Consequence Tree (C.C.T.) is utilized to analyze the primary cause and its propagation. The C.C.T. is logical tree which correlates the primary causes and the observable consequences. The algorithms for analysis of the primary cause is now major concerns. The present note concerns a proposal of this algorithm and some experimental results in an application to uranium enrichment facilities are given to show the potential usefulness of the proposal algorithm.

At first, consider the following algorithm:

(1) List the primary causes \((r_1, \ldots, r_m)\) that might activate all the alarms which are now to be analyzed.

(2) Calculate the state of every observable node \(R=(R_1, \ldots, R_n)'\) on every combination of causes \(r=(r_1, \ldots, r_m)'\) tracing the C.C.T. This procedure is formulated as

\[
R=f(r). \quad (1)
\]

(3) Search the true cause \(\hat{r}\) that minimize the distance

\[
D=(Z-R)'(Z-R),
\]

where \(Z=(Z_1, \ldots, Z_n), Z_i\) is the actual state of every observable node.

For example, the equation \(R=f(r)\) in Fig. 1 will be represented in Table 1. Suppose the cause \(A\) were occurring, then, the actual state \(Z\) would become \(Z=(1, 0)\). The estimated cause \(\hat{r}\) that gives the distance \(D(\hat{r})=0\), is \(\hat{r}=(1, 0, 0)\).

![Fig. 1 Example of C.C.T.](image)

\[
\text{Table 1 Function } R=f(r)
\]

<table>
<thead>
<tr>
<th>(r=(r_1, r_2, r_3))</th>
<th>(R=(R_1, R_2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>((1, 0, 0))</td>
<td>((1, 0))</td>
</tr>
<tr>
<td>((0, 1, 0))</td>
<td>((1, 1))</td>
</tr>
<tr>
<td>((0, 0, 1))</td>
<td>((0, 1))</td>
</tr>
<tr>
<td>((1, 1, 0))</td>
<td>((1, 1))</td>
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<tr>
<td>((0, 1, 1))</td>
<td>((1, 1))</td>
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<tr>
<td>((1, 0, 1))</td>
<td>((1, 1))</td>
</tr>
<tr>
<td>((1, 1, 1))</td>
<td>((1, 1))</td>
</tr>
</tbody>
</table>

The problem of C.C.T. is that it is essentially binary logic and, in the actual plant, the variables will not always change like in the typical way as expected in the C.C.T. One of the solutions for this problem is that the analog value of the observable variables itself be introduced into the analysis algorithm instead of the binary value. For this purpose, \(Z\) normalized in

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the following way is to be used in this algorithm.
(1) If $Z_i$ is originally binary variables such as level switch, vibration switch, $Z_i = 1$ or 0.
(2) If $Z_i$ is originally analog variables such as level indicator,
$$Z_i = 1/[1+\exp A(X_i - X_E)]$$
$$X_E = (X_N + X_A)/2,$$  \hspace{1cm} (2)
where $X_i$ is the actual value of the variable and $X_A$, $X_N$ are its alarm set point and normal value, respectively. (see Fig. 2).

By this normalization, the distance $D = (Z-R)(Z-R)$ can be considered as an index how the actually observed pattern $Z$ approaches the calculated typical pattern $R$. Therefore, the cause which gives the minimum of $D(r)$, can be regarded as the true cause.

In the algorithm mentioned above, it is likely to happen that $D(r_1)$, $D(r_2)$ have the same value. For example, in Table 1, $r_1 = (0, 1, 0)$, $r_2 = (1, 1, 0)$, —give the same $Z$ ($Z = (1, 1)$). Therefore, an additional criterion should be introduced that it is more likely that the sum of supposed primary causes is less for $r$’s that give the same value of $D(r)$. In the example of Table 1, $r = (0, 1, 0)$ is most likely to occur among the $r$’s which give $Z = (1, 1)$, because the sum of causes is minimum, i.e. 1. Thus, the whole algorithm of the cause analysis is the search of $r$ that minimizes the following evaluation function:

$$f(r) = A(r) + \alpha (Z-R)(Z-R) \hspace{1cm} \alpha : \text{const.} \hspace{1cm} (3)$$

In Eq. (3), $A(r)$ represents the total number of causes which are supposed now occurring. $f(r)$ is the summation of $A(r)$ and the above mentioned distance $D = (Z-R)(Z-R)$. Proper choice of $\alpha$ is based on trial and error adjustment.

The numerical test has been executed in an application to a cascade system of uranium enrichment facilities, in which a simplification of Eq. (1) has been taken. Since the C.C.T. of the system has no AND gates and is composed of only OR gates, the C.C.T. has been simply represented in a form of decision table $N$ as shown in Table 2 and, instead of Eq. (1), the following equation

$$R = (\max n_{11} r_1, \ldots, n_{1m} r_m), \ldots, \max n_{n1} r_1, \ldots, n_{nm} r_m) \hspace{1cm} (4)$$

has been used, where $n_{ij}$ is the element of the decision table $N$, $N = \{n_{ij}\}$, and $r_j$ the element of the combination of causes $r = (r_1, \ldots, r_m)$.

**Table 2** Decision table of cascade system

<table>
<thead>
<tr>
<th>Primary causes</th>
<th>Observable Variables</th>
<th>Emergent value indicator failure</th>
<th>Manual control valve indicator failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cascade pressure I</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Cascade pressure II</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Enriched product flow</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Waste product flow</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Vibrating and temp of centrifuge</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Feed inlet pressure</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Enrichment</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Variance from cascade model</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Manual control valve position</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Emergency exhaust valve position</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
The typical results of the numerical test are shown in Fig. 3(a) and (b) in comparison with the pseudo inverse method.

\[ \hat{r} = N^*Z. \quad (5) \]

The vector \( \hat{r} \) is the smallest one which satisfies \( Z = Nr \), i.e. \( \hat{r} \) minimizes \( J(r) = r'y. \)

In Fig. 3(a), supposing \( Z = (0.6, 0.6, 0.4, 0.4, 0, 0, 0.7, 0.7, 0, 0)' \), which represents a situation of progressing disturbance \( r_2 \) (Leakage of air into cascade system as shown in Table 2), the algorithm of Eq. (3) has precisely estimated the true primary cause. In the other example, of Fig. 3(b), supposing \( Z = (1, 1, 1, 1, 0, 1, 0, 0)' \) which represents a situation of simultaneous occurrence of the cause \( r_2 \) and \( r_7 \) (Leakage of air and failure of centrifuge), Eq. (3) has also precisely estimated both causes. On the contrary, in the pseudo inverse method the estimation is false for both examples.

The numerical test confirmed the cause analysis algorithm. The newly proposed one has a potential to precisely estimate the true causes in both the situations of progressing disturbance and of simultaneous occurrence of two causes.

--- REFERENCES ---


