A real-time identification and mitigation solution generation method of random disturbance in a manufacturing system

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Abstract
In order to timely identify and mitigate the adverse effect of the random disturbance in the manufacturing system, a method of identifying and mitigating the random disturbance is proposed. In the method, the disturbance is structured into several categories, and each is subdivided into several events. The disturbance data detected by the hardware system are normalized to 10 scales for more accurate monitoring. An evaluation model is built and it has a bi-layer criteria system, which can evaluate every category disturbance and the whole system at the same time. The fuzzy analytic hierarchy process is utilized to calculate the criteria weights and evaluate the impacts of the disturbance. Time and cost used as constraints are combined into the adjustment solution. The BP neural network is used to generate adjustment solution for the disturbance, and then the resource and task scheduler are adjusted to mitigate the loss caused by the disturbance. Finally, the proposed method is illustrated by an example, and the validity of the method is verified.

Keywords
Manufacturing system, disturbance, BP neural network, fuzzy analytic hierarchy process

Introduction
Disturbance in the manufacturing system
In the complex manufacturing system, there are various kinds of disturbances, such as order change, insufficient supply of raw materials, delay or shortage of goods, change in the production process, change of equipment status and quantity, and so on. These disturbances often result in the failure of the production plan.\textsuperscript{1} Therefore, it is very important to study the disturbance and the real-time identifying and mitigating method.

Balasubram\textsuperscript{2} defined random disturbance as a lack of accurate knowledge or prediction of a process. Zhu\textsuperscript{3} deemed that the random disturbance is caused by inaccurate information, unknown information, inherent model, subjective judgment, and so on. Wu\textsuperscript{4} deemed that the disturbance randomness rooted in manufacturing resources and the external environment. Liu et al.\textsuperscript{5} divided disturbances into the task disturbance, production process disturbance, material resource disturbance, and production executive disturbance. The above-described method of random disturbance mainly includes probability distribution description, fuzzy mathematical description, interval description, and discrete value description.\textsuperscript{6} On this

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basis, Bokrantz et al.\textsuperscript{7} proposed 21 production disturbance factors.

**Related research**

In recent years, the identifying method of disturbance has been studied. Li et al.\textsuperscript{8} studied the operating status identifying system of the digital production workshop. Chang et al.\textsuperscript{9} established a workshop production process monitoring system and developed the related software and hardware. Liu et al.\textsuperscript{10} constructed a production information monitoring model. Sun et al.\textsuperscript{11} proposed a contextual alarm of the manufacturing system, and it is described as follows

\[
A_{li} = [A_{l1}, A_{l2}, \ldots, A_{ln}], i = 1, 2, \ldots, n
\]  

The normal value of detected items is in a database, and it is described as follows

\[
v_i = [v_{i1}, v_{i2}, \ldots, v_{in}], i = 1, 2, \ldots, n
\]

where \(v_i\) is the monitoring value vector, \(v_{i1}, \ldots, v_{in}\) are the values of the criteria, and they are between 0 and 1.

The monitoring data detected and collected by the hardware monitoring system real-time is normalized into values of 10 scales between 0 and 1. They are described as

\[
v_i = [v_{i1}, v_{i2}, \ldots, v_{in}], i = 1, 2, \ldots, n
\]

where \(v_i\) is the monitoring value vector, \(v_{i1}, \ldots, v_{in}\) are the monitoring values, which between 0 and 1.

Detected values will be matched with the data in the database, and the disturbance is generated if there is a difference, as shown in Figure 1.

**Evaluation of the adverse effect**

First, an evaluation model is constructed, and second the FAHP is utilized to calculate the weight of each criterion and its event. Third, the evaluation value of each criterion is obtained by multiplying and adding the events’ value and the events’ weight. Finally, the evaluation index of the manufacturing system is calculated by multiplying and adding the criteria’s values and its weight.

**Evaluation model**

An example of the evaluation model is shown in Figure 2. There are five criteria, such as planning task, material resource, manufacturing process, manufacturing resource, and personnel change.

In Figure 2, the criteria are described by a vector shown as follows

\[
At = [At_{IT}, At_{IR}, At_{IP}, At_{IM}, At_{IR}]
\]

Each criterion includes several events, which are shown as follows

\[
At_{IT} = [At_{IT1}, At_{IT2}, At_{IT3}, At_{IT4}, At_{IT5}]
\]

\[
At_{IR} = [At_{IR1}, At_{IR2}, At_{IR3}, At_{IR4}]
\]
Calculated the weight

The theory of fuzzy mathematics is applied to the analytic hierarchy process, so it can be used as a basis for evaluation and decision-making through quantitative analysis. For the complementary fuzzy judgment matrix \( A = (a_{ij})_{n \times n} \), the matrix \( \overline{A} = (\overline{a}_{ij})_{n \times n} \) is called the synthesis matrix of the matrix \( A \). It is calculated by \( \overline{A} = \lambda_1 A_1 \oplus \lambda_2 A_2 \oplus \cdots \oplus \lambda_n A_n \), where \( r_i = \sum_{j=1}^{n} a_{ij}, (i = 1, 2, \ldots, n) \) is used to calculate the sum of each row in the matrix \( A = (a_{ij})_{n \times n} \), and according to the equation \( r_j = ((r_i - r_j)/2(n-1)) + 0.5 \), then get consistent fuzzy matrix \( R = (r_{ij})_{n \times n} \). Finally, the unit eigenvectors of this consistent fuzzy matrix are obtained by the normalizing rank aggregation (NRA), and it is calculated by \( \omega_i = ((\sum_{j=1}^{n} a_{ij} + (n/2) - 1)/(n(n-1))), \ i = 1, 2, \ldots, n \). Then the sorted vector is a weight vector.

Calculation of the evaluation value of each criterion. The evaluation value of each criterion is described by \( f_i \) calculated by the following equation

\[
f_i = |At_i| \cdot \omega_{Bi} = \sum_{j=1}^{n} |At_{ij}| \times \omega_{Bij}, i \in [1, 2, \ldots, m]
\]

where \( f_i \) indicates the index of the \( i \) criterion. \( \omega_{Bi} \) is the weight of each event of the \( i \) criterion. \( m \) is the quantity of evaluation criteria.

Calculation of the evaluation index of the whole manufacturing system. The weight vector of criteria is expressed as

\[
\omega_A = [\omega_1, \ldots, \omega_i, \ldots, \omega_m]^T
\]

where \( \sum_{i=1}^{m} \omega_i = 1 \), \( \omega_i \) is the weight of \( i \) criterion.
$f = (f_1, f_2, \ldots, f_m)$ is defined to describe the evaluation index vector. The index $E_T$ is the evaluation value of the whole system, which is calculated by the following equation

$$E_T = f \cdot \omega_A = \sum_{i=1}^{m} f_i \times \omega_i$$

(12)

The smaller the value of $E_T$, the smaller the disturbance. The greater its value, the greater the damage of the system.

**Generation of mitigation solution based on BP neural network**

**Adjustment method of the disturbance**

When the disturbance emerges, one or more methods are selected as adjustment methods to mitigate the impact of disturbance. Different methods are developed according to the experience of experts. Some methods are presented in Table 1.

Different disturbance has different adverse effects on the system, and has different mitigating methods. Some disturbance events and mitigation methods are shown in Table 2.

**Definition of mitigation solution**

There is more than one method to mitigate a disturbance, and one method may have an effect on more than one disturbance. In order to select the appropriate solution for each disturbance, there are two constraints used to select a method, and they are time and cost. The time or cost of the same method may differ for different workshops. By adjusting time and cost, we have more flexibility in choosing methods. Therefore, time and cost are integrated with two alternative approaches to constitute a solution for one category of disturbance, which can be defined as

$$A_{di} = [A_{di1}, A_{di2}, A_{di3}, A_{di4}]$$

(13)

where $A_{di1}, A_{di2}$ are the time and the cost, respectively. $A_{di3}, A_{di4}$ represent the approach, respectively.

**Generation of the mitigation solution**

The disturbance is randomness and complexity, and it is difficult to establish a very accurate mathematical model. A neural network is a kind of intelligent methods and can implement the most nonlinear mapping

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**Table 1. Adjustment methods for the disturbance.**

| Methods | Description |
|---------|-------------|
| 1       | Replace the current manufacturing unit |
| 2       | Replace the original processing technology by one or more techniques |
| 3       | Increase production capacity |
| 4       | Change the priority of production tasks |
| 5       | Add the equipment or outsource |
| 6       | Urgently purchase some raw materials |
| 7       | Train the staff |
| 8       | Assign some workers to work overtime or temporarily replacement |

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**Table 2. Disturbance events and adjustment methods.**

| Disturbance events | Impact of disturbance | High priority methods | Low priority methods |
|--------------------|-----------------------|-----------------------|---------------------|
| Emergency order    | Task conflict for the manufacturing unit | 4                     | 3                   |
| Order cancel       | A manufacturing unit is hidde | 4                     | 1                   |
| Order in advance   | Task conflict or manufacturing unit is hidde | 4                     | 3                   |
| Order delay        | A manufacturing unit is hidde | 4                     | 1                   |
| Order priority changes | Task conflict or disorder of the manufacturing unit | 4                     | 2                   |
| Raw material shortage | Production delay or failure | 6                     | 7                   |
| Outsourcing component shortage | Production delay or failure | 6                     | 7                   |
| Auxiliary material shortage | Production delay or failure | 6                     | 7                   |
| Material disqualification | Production delay or failure | 6                     | 7                   |
| Process sequence change | New logistics path emerged | 4                     | 1                   |
| Process reduction  | Original logistics path disappearance | 4                     | 2                   |
| Process increase   | New logistics path emerged | 4                     | 1                   |
| Device fault       | Production task is aborted or delayed | 4                     | 2                   |
| Device repair      | Production task is aborted or delayed | 4                     | 1                   |
| Device increase    | New logistics path emerged | 4                     | 1                   |
| Device reduction   | Task conflict or abort | 2                     | 1                   |
| Tooling time delay | Production delay | 4                     | 1                   |
| Operators absenteeism | Production task is aborted or delayed | 1                     | 8                   |
| Operation error    | Production delay | 4                     | 7                   |
| Operators’ skill level is poor | Production delay | 4                     | 7                   |
Table 3. Disturbance and changes of the production task in a workshop.

| Changes in planned tasks | Rush order | Order cancel | Order in advance | Order delay | Order priority changes |
|-------------------------|------------|--------------|------------------|-------------|-----------------------|
|                         | Six rush orders have been issued | Eight orders canceled | Five orders need to be made in advance | Seven orders need to be delayed | The priority of seven orders has changed |
| Quantification of change | 0.6        | -0.8         | 0.5              | -0.7        | 0.7                   |
| Normal data             | 0          | 0            | 0                | 0           | 0                     |
| Disturbance             | 0.6        | -0.8         | 0.5              | -0.7        | 0.7                   |

Step 1: When the adverse effect of one category disturbance or the whole manufacturing system exceeds the threshold, the anti-disturbance system will operate automatically. The detected disturbance is matched first to the disturbance in the database, and if there is the same disturbance, the anti-disturbance system goes to step 2, otherwise, it goes to step 3.

Step 2: According to the disturbance, search the corresponding method from the method database. If it can execute automatically, it will be executed automatically. Otherwise, it goes to step 4 and submits the solutions to the operator.

Step 3: Based on the disturbance, the neural network is started to generate the new mitigation method, and the generated method is submitted to the operator and the system goes to step 4.

Step 4: The method is judged and modified by the operator, and executed according to the modified method to eliminate the effect of the disturbance, and the modified new method is stored in the database.

Step 5: Judge whether the effect of the disturbance is eliminated, if yes, the program ends, otherwise goes to step 2.

Application example

The example mentioned in section “Evaluation model” is used to illustrate the proposed methods. There are five categories disturbance described in section “Evaluation model,” and the evaluation model is presented in Figure 2. The monitoring data are acquired by the digital twin-driven manufacturing cyber-physical system. So, we’ve got the disturbance data as shown from equations (14)–(18). Then, the weight of each category of disturbance and each event in the disturbance is calculated first. Second, the adverse effect value of each type of disturbance and all disturbances on the system are calculated. Third, it is determined whether the value of the adverse effect exceeds the threshold. Fourth, for the disturbance that exceeds the threshold, the mitigation method is solved. Finally, on the basis of the generated method, the adverse effect of the disturbance is eliminated automatically or manually. The detailed steps are outlined in the following paragraphs.

Disturbance identification

By comparing the variation of evaluation criteria with the normal data, the disturbance is identified as mentioned in section “Identification of disturbance.” In this case, the values of planned task events are changed and these are quantified by the operator to compare with the normal value, so the disturbance of the planned task is generated as shown in Table 3.

The identified disturbance of the planned task is described with vector as follows

\[ \text{At}_{IT} = [\text{At}_{IT1}, \text{At}_{IT2}, \text{At}_{IT3}, \text{At}_{IT4}, \text{At}_{IT5}] = [0.6, -0.8, 0.5, -0.7, 0.7] \]  

By the same way, the disturbances of other criteria are described with vector as follows

\[ \text{At}_{IR} = [\text{At}_{IR1}, \text{At}_{IR2}, \text{At}_{IR3}, \text{At}_{IR4}] = [0, 0.3, 0, 0] \]  

\[ \text{At}_{IP} = [\text{At}_{IP1}, \text{At}_{IP2}, \text{At}_{IP3}] = [0.2, 0, 0.1] \]  

\[ \text{At}_{IM} = [\text{At}_{IM1}, \text{At}_{IM2}, \text{At}_{IM3}, \text{At}_{IM4}, \text{At}_{IM5}] = [0.2, 0, -0.1, 0.1, 0.1] \]  

\[ \text{At}_{IW} = [\text{At}_{IW1}, \text{At}_{IW2}, \text{At}_{IW3}] = [0.2, 0, 0.1] \]

Calculation of the weight

As mentioned in section “Calculation of the weight,” FAHP is used to calculate the weight of each criterion and its event. Two manufacturing experts are hired to
The weight of each criterion is obtained using the NRA judgment matrix. They have equal weight and each is 0.5. Therefore, two complementary fuzzy matrices are obtained as follows:

\[
A_1 = \begin{bmatrix}
IT & IR & IP & IM & IW \\
0.5 & 0.3 & 0.2 & 0.4 & 0.5 \\
0.7 & 0.5 & 0.7 & 0.4 & 0.5 \\
0.8 & 0.3 & 0.5 & 0.7 & 0.6 \\
0.6 & 0.6 & 0.3 & 0.5 & 0.4 \\
0.5 & 0.5 & 0.4 & 0.6 & 0.5 \\
\end{bmatrix}
\]

\[
A_2 = \begin{bmatrix}
IT & IR & IP & IM & IW \\
0.5 & 0.6 & 0.7 & 0.5 & 0.7 \\
0.4 & 0.5 & 0.4 & 0.5 & 0.4 \\
0.3 & 0.6 & 0.5 & 0.3 & 0.5 \\
0.5 & 0.5 & 0.7 & 0.5 & 0.4 \\
0.3 & 0.6 & 0.5 & 0.6 & 0.5 \\
\end{bmatrix}
\]

\[\begin{align*}
f_{IT} &= |A_{IT}| \times \omega_{BIT} = [0.6, -0.8, 0.5, -0.7, 0.7] \\
&= [0.2375, 0.2275, 0.1685, 0.2215, 0.145] \\
&= 0.6547 \\
\end{align*}
\]

Similarly, we can calculate the evaluation value of other criteria. Therefore, the evaluation index vector is

\[
f = (f_{IT}, f_{IR}, f_{IP}, f_{IM}, f_{IW}) = [0.6547, 0.09675, 0.07182, 0.09005, 0.09] \\
\]

The evaluation index vector \( f \) is multiplied by its weight \( \omega_A \) and then added together to get the system index \( E_T \), and the equation is

\[
E_T = f \cdot \omega_A = [0.6547, 0.09675, 0.07182, 0.09005, 0.09] \\
\]

\[
\begin{bmatrix}
0.19843 \\
0.2 \\
0.2 \\
0.2 \\
0.2 \\
\end{bmatrix} = 0.199747 \\
\]

In order to more clearly describe the relationship between the disturbance, the status values of each disturbance are summarized in Table 4.

**Judgment of the adverse effect**

The threshold is used to judge the adverse effect. If the values of the system index and single category disturbance exceed the threshold, this indicates that the system is seriously disturbed and needs to be adjusted. In this case, the system index threshold \( T_E \) is set to 0.2, and the disturbance threshold \( T_I \) is set to 0.4. Although \( E_T < T_E \) indicate the whole system isn’t adjusted, but \( f_{IT} > T_I \) indicates the planned task disturbance has serious adverse effects and should be adjusted.

**Generation of the mitigation solution**

Based on the adjustment solution defined in section “Definition of mitigation solution,” a three-layer BP neural network is used to generate the adjustment solution for the disturbance. In this case, the planned task disturbance should be adjusted. Some training samples are shown in Table 5.

The planned task disturbance consists of five events. Therefore, the BP neural network input layer node number is five. The data range of the input vector is –1 to 1. The hidden layer node selects the S-type tangent function Tansig. The adjustment solution has four
parameters. Therefore, the output layer consists of four nodes. The output layer node can select the S-type logarithmic function Logsig.

Because the BP neural network of a single hidden layer can approach an arbitrary continuous nonlinear function, so it is adopted. The number of nodes in the hidden layer directly affects the nonlinear predictive ability of the network, so more nodes are utilized here. The number of nodes in the hidden layer is set to 20, and the neural network module in MATLAB is used for analysis. The BP network structure to generate the adjustment solutions is constructed, as shown in Figure 3.

In Table 5, the last disturbance is the same disturbance that we’re going to calculate. Therefore, the first 14 rows of data in Table 5 are selected as training samples, and the last row data are used as the verified data. The training variation curve of the neural network is given in Figure 4.

After the training, the disturbance data \(At_{IT} = [0.6, 0.8, -0.5, 0.7, 0.7]\) is inputted, and the output is \[8.81, 31.45, 4.02, 2.78\], which is similar to the

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### Table 4. Weight and value of the disturbance.

| Disturbance category | Weight \( (\omega_A) \) | Evaluation value | Events | Weight \( (\omega_B) \) | Identified value |
|----------------------|-------------------------|------------------|--------|------------------------|----------------|
| Plan task \((At_{IT})\) | 0.1984 | 0.6547 | IT1: emergency order | 0.2375 | 0.6 |
| Material resource \((At_{IR})\) | 0.2 | 0.09675 | IT2: order cancel | 0.2275 | 0.8 |
| Production process \((At_{IP})\) | 0.20157 | 0.07182 | IT3: order in advance | 0.2215 | -0.5 |
| Manufacturing resource \((At_{IM})\) | 0.2 | 0.09005 | IT4: order delay | 0.1685 | 0.7 |
| Personnel change \((At_{IW})\) | 0.2 | 0.09 | IT5: order priority changes | 0.145 | 0.7 |

---

### Table 5. Adjustment solution of the planned task disturbance.

| Disturbance of the planned task \((At_{IT})\) | Adjustment solution | Time | Cost | Higher priority methods | Lower priority methods |
|---------------------------------------------|---------------------|------|------|-------------------------|-----------------------|
| \([0.1 \ 0.1 \ 0.2 \ 0.1 \ 0.9]\)           |         | 2    | 9    | 4                       | 2                     |
| \([-0.2 \ 0.1 \ 0.1 \ 0.1]\)              |         | 9    | 4    | 4                       | 1                     |
| \([0.1 \ 0.1 \ 0.9 \ 0.1 \ 0.1]\)         |         | 4    | 10   | 4                       | 3                     |
| \([0.1 \ 0.8 \ 0.1 \ 0.2 \ 0.1]\)         |         | 12   | 6    | 4                       | 1                     |
| \([0.8 \ 0.1 \ 0.1 \ 0.1 \ 0.1]\)         |         | 3    | 12   | 4                       | 3                     |
| \([0.9 \ 0.1 \ 0.1 \ 0.1 \ 0.1]\)         |         | 6    | 20   | 4                       | 3                     |
| \([0.1 \ 0.1 \ 0.9 \ 0.9 \ 0.2]\)         |         | 12   | 14   | 4                       | 1                     |
| \([-0.1 \ 0.9 \ 0.1 \ 0.2 \ 0.1]\)        |         | 15   | 14   | 4                       | 1                     |
| \([0.1 \ 0.1 \ 0.9 \ 0.2]\)              |         | 21   | 11   | 4                       | 2                     |
| \([0.1 \ 0.1 \ 0.8 \ 0.2 \ 0.9]\)         |         | 7    | 18   | 4                       | 3                     |
| \([0.9 \ 0.1 \ 0.8 \ 0.1 \ 0.1]\)         |         | 6    | 22   | 4                       | 3                     |
| \([-0.1 \ 0.9 \ 0.8 \ 0.2 \ 0.9]\)        |         | 18   | 24   | 4                       | 2                     |
| \([0.8 \ 0.1 \ 0.2 \ 0.9 \ 0.9]\)         |         | 16   | 24   | 4                       | 3                     |
| \([0.1 \ 0.9 \ 0.9 \ 0.8 \ 0.1]\)         |         | 24   | 20   | 4                       | 1                     |
| \([0.6 \ 0.8 \ -0.5 \ 0.7 \ 0.0.7]\)      |         | 9    | 32   | 4                       | 3                     |
mitigation solution \([9, 32, 4, 3]\) in the last row of Table 4. So, the result is effective.

Conclusion

In the article, a method for identifying real-timely disturbance and generating an adjustment solution is offered. The detected data are described by 10 scales to improve the detection accuracy. The evaluation model realized bi-layer monitor. It can not only monitor the adverse effect of a single category disturbance, but also monitor the health status of the whole system. Time and cost are combined into the adjustment solution, and this makes the choice of solution more rational and flexible. Depending on the proposed method, the disturbance can be disposed in advance, so as to make the healthy operation of the manufacturing system.

But, the implementation of the method requires a manufacturing cyber-physical system. Therefore, in the subsequent work, the hardware and software should be developed and the real-time data detected by the hardware should be processed to 10 scales. Current research to further work is underway.

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