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Original Article

# Handling dependencies among performance shaping factors in SPAR-H through DEMATEL method

Zhihui Xu [a], Shuwen Shang [b], Xiaoyan Su [b,*], Hong Qian [b], Xiaolei Pan [b]

[a] State Key Laboratory of Nuclear Power Safety Monitoring Technology and Equipment, Shenzhen, 518172, China
[b] School of Automation Engineering, Shanghai University of Electric Power, Shanghai, 200090, China

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ABSTRACT

The Standardized Plant Analysis Risk-Human Reliability Analysis (SPAR-H) method is a widely used method in human reliability analysis (HRA). Performance shaping factors (PSFs) refer to the factors that may influence human performance and are used to adjust nominal human error probabilities (HEPs) in SPAR-H. However, the PSFs are assumed to be independent, which is unrealistic and can lead to unreasonable estimation of HEPs. In this paper, a new method is proposed to handle the dependencies among PSFs in SPAR-H to obtain more reasonable results. Firstly, the dependencies among PSFs are analyzed by using decision-making trial and evaluation laboratory (DEMATEL) method. Then, PSFs are assigned different weights according to their dependent relationships. Finally, multipliers of PSFs are modified based on the relative weights of PSFs. A case study is illustrated that the proposed method is effective in handling the dependent PSFs in SPAR-H, where the duplicate calculations of the dependent part can be reduced. The proposed method can deal with a more general situation that PSFs are dependent, and can provide more reasonable results.


## 1. Introduction

Human reliability analysis (HRA) analyzes human reliability qualitatively and quantitatively, and evaluates the impact of human failure on system failure, so as to predict human error probability (HEP) and reduce human failure event (HFE). HRA is an indispensable part of Probabilistic Safety Assessment (PSA) of nuclear power plants. Various methods have been developed for HRA, such as the Technique for Human Error Rate Prediction (THERP) [1], the Human Error Assessment and Reduction Technique (HEART) [2], the Cognitive Reliability and Error Analysis Method (CREAM) [3], etc. Among them, SPAR-H has been widely used in various fields (such as petroleum industry [4,5], offshore emergency response [6], chemical industry [7], occupational risk [8] and other fields) due to its advantages of simple model, reliability and convenience [9].

In SPAR-H, PSFs with different levels (multipliers) are used to modify nominal HEPs to better quantify the error probabilities in specific scenarios. However, the process of calculating HEP by SPAR-H is based on the assumption that PSFs are independent of each other, which is inconsistent with the actual situation. For example, the PSFs "complexity" and "stress/stressors" suggested by SPAR-H are dependent: as the "complexity" increases, the "stress/stressors" increases accordingly. Therefore, the influence of the correlative parts of the PSFs on HEP is calculated repeatedly, which may lead to overestimation or underestimation of the results.

In HRA, dependences can be divided into three categories: dependences between human failure events (HFEs) (CAT1), dependences between HEP and PSFs (CAT2), and dependences between PSFs (CAT3) [10]. For CAT1 dependences, Cepin et al. [11] developed a method to model the dependencies among consecutive human actions based on scenarios. Vincent P. Paglioni et al. [12] pointed out the limitations of the dependency framwork established in the THERP and proposed a standardized library of key terms and mathematics to provide a basis for the development of a dependency framework. For CAT2 dependences, most HRA methods calculate HEP through PSF multipliers, such as HEART and SPAR-H. For CAT3 dependences, in recent years, the dependence of PSFs in HRA has received more and more concerns [10,13–15].

Various methods are provided to deal with the dependent PSFs in SPAR-H method. Laumann and Rasmussen [16] pointed out that the definitions and descriptions of PSFs used in SPAR-H were unclear and overlap too much, and thus suggested new definitions of PSFs, levels and multipliers to increase the inter-rater reliability and

* Corresponding author.
*E-mail address:* suxiaoyan@shiep.edu.cn (X. Su).

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improve the capacity of SPAR-H. Liu [17] improved the PSF multiplier design in SPAR-H based on absolute probability judgment (APJ) and ratio magnitude estimation (RME), which can strengthen the empirical and psychological foundations of SPAR-H. However, the newly defined PSFs could also have interdependence among them, such as "Available time" and "Stress/Stressors". Liu [18] studied the dependencies among PSFs based on data mining methods (i.e., association rule analysis, exploratory factor analysis and Pearson correlation analysis), and divided the eight PSFs into two categories. However, the data mining methods require a large amount of data, which may be unavailable in some cases. Also, the data mining methods, such as Pearson correlation analysis, only capture linear correlations among variables which may be insufficient in handling actual situations. Liu [19] applied an interesting system dynamics approach based on mutual information theory and analytic hierarchy process to model the dependencies of PSFs and provided deeper insight into this problem. However, the model based on mutual information theory may be inaccurate due to a lack of available data and the quantification of HEPs based on PSFs is complicated. Ref. [20] provides pair-wise comparison of relative relationship among PSFs in the form of matrix based on expert opinions. It provides good reference for the analysis of the dependence among PSFs. However, only qualitative analysis of the relative relationships among PSFs is given, which cannot be used in the calculation of HEP directly.

Based on the above analysis, we can see that, the current methods dealing with the dependent PSFs in SPAR-H provided deeper insights of the problem and valuable suggestions in defining new PSFs. However, problems still exist in the modeling of dependences among PSFs and no convenient and practical method of calculating HEPs is provided. The objectives of this paper are to provide an effective method for modeling the dependences among PSFs and to provide an applicable method for calculating HEPs which considers the dependences among PSFs.

The methodology of the Decision Making Trial and Evaluation Laboratory (DEMATEL) is a method proposed by scholars from Battelle Laboratory in the United States at a conference in Geneva in 1971. It is an effective method to analyze the direct and indirect relations among the factors in the system, and it can determine the position of each factor in the system, and is mainly used for the selection of important factors [21]. DEMATEL is widely used in supply chain management [22–25], waste management [26–28], disaster risk management [29,30] and other fields. In this paper, we propose a method to express and process PSFs dependence in SPAR-H based on DEMATEL method, and provide an improved HEP calculation method accordingly. The relative relationship matrix of PSFs suggesed by Ref. [20] is applied as input data in this paper to describe the relative relationships among PSFs. DEMATEL is used to deal with the input dependence data (relative relationship matrix of PSFs) to obtain the weights of the PSFs. A method is then proposed to modify the HEP based on the weights of the PSFs.

This paper is organized as follows. Section 2 introduces the basic theories of SPAR-H and DEMATEL. Section 3 describes the specific flow of the proposed method. In Section 4, effectiveness of the method is shown by the case study. Section 5 concludes the paper.

## 2. Preliminaries

### 2.1. SPAR-H

The PSF system of SPAR-H is one of the most distinctive features of this method. It considers eight PSFs, which are: Available time, Stress/stressors, Complexity, Experience/training, Procedures, Ergonomics/human machine interaction (HMI), Fitness for duty, and Work processes. SPAR-H provides a method to calculate HEP, based on the nominal human error probability (NHEP), and the eight PSFs. The process of calculating the HEP using SPAR-H method is as follows. First, the analyst analyzes the HFE, determines the PSF category and the level to which it belongs, and obtains the corresponding PSF multipliers according to Table 1 [20]. The application of PSF multipliers follows a "threshold approach," wherein discrete multipliers are used that are associated with various PSF levels. Since these are thresholds, the multipliers do not convey information regarding the uncertainty associated with the multiplier [20]. Then, HEP can be obtained by multiplying these multipliers with the NHEP as is shown in Eq. (1) [20].

$$HEP = NHEP \cdot \prod_{i=1}^{8} S_{PSF_i} \tag{1}$$

where NHEP $=0.01$ for diagnosis and NHEP $=0.001$ for action. $S_{PSF_i}$ is the multiplier of the $i$th PSF.

When there are more than three PSFs with negative effects, the correction formula of HEP is as follows:

$$HEP = \frac{NHEP \times \prod_{i=1}^{8} PSF_i}{NHEP\left(\prod_{i=1}^{8} PSF_i - 1\right) + 1} \tag{2}$$

The final HEP is the sum of the HEP for diagnosis and the HEP for action.

### 2.2. DEMATEL

The basic steps of DEMATEL are as follows [31,32].

**Step 1.** A group of experts/analysts evaluates the relationship/dependence between sets of paired alternatives and obtains a matrix of direct relations $M = [a_{ij}]$, which is the initial data of the DEMATEL analysis.

**Step 2.** According to Eq. (3) and Eq. (4), the matrix $M$ is normalized to obtain the normalized direct relation matrix $N$.

$$s = max_{i=1}^{n}\left(\sum_{j=1}^{n} a_{ij}\right) \tag{3}$$

$$N = \frac{M}{s} \tag{4}$$

where $a_{ij}$ is the element in row $i$ and column $j$ of matrix $M$. $s$ is the row sum maximum value in the matrix $M$.

**Step 3.** The total relation matrix $T$ which consists of direct and indirect relations between alternatives is obtained from the normalized direct relation matrix $N$. The calculation formula is as follows.

$$T = \lim_{k\to\infty}(N + N^2 + \cdots + N^k) = N(I - N)^{-1} \tag{5}$$

The sum of the rows in the matrix of $T$ is called influence degree $R$, which represents the comprehensive influence degree of the factors corresponding to each row on all other factors. The sum of each column is called the affected degree $C$, which indicates the degree that the factors corresponding to each column are comprehensively influenced by all other factors.

**Step 4.** The value of $R-C$ is used to indicate the degree of influence of one alternative on all other alternatives. Alternatives having higher values of $R-C$ have higher influence to others. The value of $R + C$ is used to indicate degree of dependence between one

**Table 1**
Values of 8 PSFs under low power and shutdown condition.

| SPAR-H PSFs | Diagnosis | | Action | |
|---|---|---|---|---|
| | SPAR-H PSF Levels | SPAR-H Multipliers | SPAR-H PSF Levels | SPAR-H Multipliers |
| Available Time | Inadequate Time | P(failure) = 1.0 | Inadequate Time | P(failure) = 1.0 |
| | Barely adequate time (≈2/3 × nominal) | 10 | Time available ≈ the time required | 10 |
| | Nominal time | 1 | Nominal time | 1 |
| | Extra time (≤2 × nominal) | 0.1 | Time available ≥5 × the time required | 0.1 |
| | Expansive time (> 2 × nominal) | 0.1 to 0.01 | Time available is ≥ 50 × the time required | 0.01 |
| Stress/Stressors | Extreme | 5 | Extreme | 5 |
| | High | 2 | High | 2 |
| | Nominal | 1 | Nominal | 1 |
| Complexity | Highly complex | 5 | Highly complex | 5 |
| | Moderately complex | 2 | Moderately complex | 2 |
| | Nominal | 1 | Nominal | 1 |
| | Obvious diagnosis | 0.1 | | |
| Experience/Training | Low | 10 | Low | 3 |
| | Nominal | 1 | Nominal | 1 |
| | High | 0.5 | High | 0.5 |
| Procedure | Not available | 50 | Not available | 50 |
| | Incomplete | 20 | Incomplete | 20 |
| | Available, but poor | 5 | Available, but poor | 5 |
| | Nominal | 1 | Nominal | 1 |
| | Diagnostic/symptom oriented | 0.5 | | |
| Ergonomics/HMI | Missing/Misleading | 50 | Missing/Misleading | 50 |
| | Poor | 10 | Poor | 10 |
| | Nominal | 1 | Nominal | 1 |
| | Good | 0.5 | Good | 0.5 |
| Fitness for duty | Unfit | P(failure) = 1.0 | Unfit | P(failure) = 1.0 |
| | Degraded Fitness | 5 | Degraded Fitness | 5 |
| | Nominal | 1 | Nominal | 1 |
| Work Process | Poor | 2 | Poor | 5 |
| | Nominal | 1 | Nominal | 1 |
| | Good | 0.8 | Good | 0.5 |

alternative and all other alternatives. Alternatives having higher values of $R+C$ are more correlated with others.

## 3. The proposed approach

The flow chart of the proposed method is as shown in Fig. 1, and the procedures are introduced step by step as follows.

**Step 1.** Determine experts involved in the evaluation

Experts having professional experience and relevant knowledge in nuclear power plant are selected to participate in the evaluation.

**Step 2.** Suggest dependence degree between every two PSFs

A set of dependence degree levels and their corresponding numerical values adopted is presented in Table 2. The values are used to evaluate the relationship between sets of paired PSFs, the bigger the value the stronger the dependence. If the value equals 0, it means that no dependence exists between these two PSFs. In this paper, numerical value (comparison scale) varying from 0 to 9 is adopted since it is better fit for the relationships among eight PSFs in SPAR-H which includes dependence degrees "high", "medium to high", "medium", "low to medium", "low" and "zero". Experts suggest dependence degree between every two PSFs according to Table 2. Thus, the initial inputs of the direct relations matrix $M$ in DEMATEL can be obtained.

**Step 3.** Calculate the relative weights of the PSFs

According to Eq. (3) and Eq. (4), the normalized direct relation matrix $N$ can be obtained. Then, the total relation matrix $T$ can be calculated based on Eq. (5). By calculating the row sum and column sum of matrix $T$, the value of $R-C$ can be obtained. In DEMATEL, the value of $R-C$ is more effective than $R+C$ to represent the influences (cause and effect) between alternatives. Thus, in this paper, we propose a method of deriving relative weights of PSFs based on the value of $R-C$.

The value of $R-C$ indicates the importance of a certain PSF, which is a calculation of the comprehensive influence degree of the PSF on all other PSFs ($R$) minus the degree of the PSF influenced by all other PSFs ($C$). PSFs with higher values of $R-C$ have greater influences on others and are less affected by others, and thus have larger weights. Note that the value of $R-C$ could be positive or negative. If we arrange the values of $R-C$ on a number axis, the values as well as the weights (of the corresponding PSFs) increase from left to right.

If the values of $R-C$ are all positive, then the relative weights of the PSFs can be calculated by Eq. (6). If there are negative values of $R-C$, this paper proposes a method to deal with it by offsetting $R-C$, as is shown in Eq. (7). The physical meaning of the offset $\sum_{i=1}^{8}|(R_i-C_i)|$ is the sum of the absolute values of all $R-C$. The offset defined here is to achieve the following two objectives: the negative R−C values can be mapped into positive values by adding the offset and thus can be used directly for calculating weights of PSFs; the closer the R−C value to the left of the number axis, the smaller the corresponding positive value, and thus the less the weight of the corresponding PSF. Note that Eq. (7) is one possible solution to deal with the negative R−C values. Other mathematical models could be further investigated in the future.

The specific flow is to first take the absolute value of all $R-C$ and take the sum of the absolute values as the offset. Each $R-C$ plus the offset which is called the modified value $O$, and the modified value

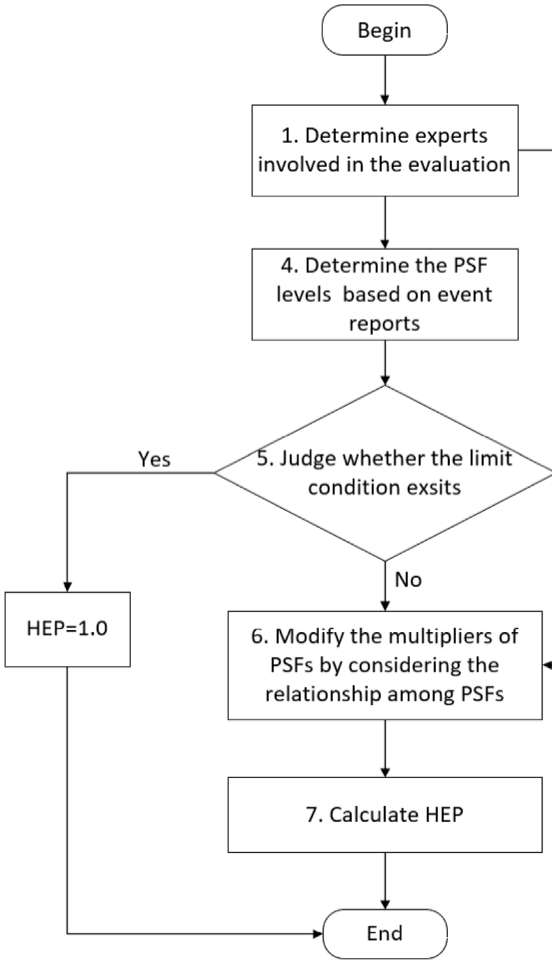


**Fig. 1.** Flow chart of the proposed method.

**Table 2**
Levels of dependence degree and their corresponding numerical values.

| Dependece degree | Numerical value |
|---|---|
| High | 9 |
| medium to high | 7 |
| medium | 5 |
| low to medium | 3 |
| Low | 1 |
| Zero | 0 |

is normalized by Eq. (8) to obtain the relative weight of each PSF. At this point, Eq. (6) is modified to Eq. (8). The weights will be used as discount coefficients to modify the multipliers of PSFs in Step 6.

$$w_i = (R_i - C_i)/\max_i(R_i - C_i) \tag{6}$$

$$O_i = (R_i - C_i) + \sum_{i=1}^{8}|(R_i - C_i)| \tag{7}$$

$$w_i = O_i/\max_i O_i \tag{8}$$

where $w_i$ is the relative weight of the $i$th PSF, $O_i$ is the $i$th modified value of $R-C$ after offsetting.

**Step 4.** Determine the PSF levels

Experts analyze event reports to determine the level of PSFs based on their expertise and experience according to the descriptions such as that in Table 1.

**Step 5.** Judge whether the limit condition exsits

As is shown in Table 1, when the level of PSF ''Available Time'' lies in ''Inadequate Time'', or when the level of PSF ''Fitness for Duty'' lies in ''Unfit'', HEP = 1, and the process ends. Otherwise the process will be continued with the following steps.

**Step 6.** Modify the multipliers of PSFs

Considering the dependence/relationship among PSFs, Eq. (9) is used to modify the multipliers of PSFs to reduce the influence of the repeated calculation of the correlative part among PSFs on HEP. The basic idea of Eq. (9) is that if a certain PSF has a greater weight, which means the PSF is more important (or has greater influence on others and is less affected by others), the corresponding original multiplier of the PSF plays more important role in the adjustment of the HEP (i.e., the modified multiplier $\alpha*$ is closer to the original multiplier $\alpha$). Let's discuss two extreme cases. Assuming that one PSF is completely correlated with other PSFs, which contains no independent information and has a weight of 0. According to Eq. (9), the modified multiplier of the PSF is 1, and thus the PSF has no influence on HEP according to Eq. (1) and Eq. (2). Assuming that one PSF is completely independent from other PSFs (that is, the assumption of classical SPAR-H), and has a weight of 1. According to Eq. (9), the modified multiplier of the PSF equals the original multiplier, and thus affects the adjustment of HEP according to Eq. (1) and Eq. (2). From the above analysis, it can be found that Eq. (9) is flexible in modifying the multipliers of the PSFs. When all the PSFs are independent, Eq. (9) is also compatible with the classic SPAR-H.

$$\alpha_i^* = w_i \cdot \alpha_i + (1 - w_i) \times 1 \quad (9)$$

where $\alpha_i$ is the original multiplier corresponding to the level of the $i$th PSF suggested by experts according to Table 1, and $w_i$ is the relative weight of the $i$th PSF obtained in Step 3. $\alpha_i^*$ is the modified multiplier of the $i$th PSF.

**Step 7.** Calculate HEP

Using Eq. (1) or Eq. (2) to calculate HEP. Note that the multiplier $S_{PSFi}$ is replaced by the modified multiplier $\alpha_i^*$ derived in Step 6.

## 4. Case study

In this section, the HRA worksheet of the event "Failure to Recover RHR" in "Loss of Inventory with RCS Pressurized" for LP/SD [20] is used to illustrate the procedures of the proposed method. Then, additional cases with different PSF multipliers are designed to show the effectiveness of the proposed method.

### *4.1. Procedures of the proposed method*

**Step 1.** Selection of experts

The experts have been selected in the area of HRA with professional experience or knowledge in the nuclear power plants. Note that no concrete implementation of this step is carried out in the study, the data source is based on the opinions of experts from Ref. [20], which is enough for presenting the use of the proposed method.

**Step 2.** Suggest dependence degree

According to NUREG CR-6833 [20], we can draw a conclusion about the relative relationships among SPAR-H PSFs (as is shown in Table 3). Note that in Table 3, the element shows the influence of $X$ upon $Y$, while the element $M_{ij}$ of DEMATEL's initial input matrix represents the influence of $Y$ upon $X$. Therefore, we need to transpose $X$ and $Y$ in Table 3 to gain Table 4. Table 4 is used as the input source for DEMATEL. Then the direct relation matrix (as is shown in Table 5) can be obtained by quantifying the dependence degree based on Table 2 in Step 2 in Section 3.

**Step 3.** Calculate the relative weight of the PSFs

We use Eq. (3) and Eq. (4) to normalize matrix $M$, and use Eq. (5) to get the total relation matrix $T$, and calculate $R$,$C$. The negative $R-C$ is offset based on Eq. (7), and the relative weights of PSFs are calculated according to Eq. (8). The results are shown in Table 6.

**Step 4.** Determine the PSF levels

According to Appendix D in Ref. [20], the levels and multipliers of the PSFs for the diagnosis portion and action portion of the task "Recover RHR" are shown in Table 7 and Table 8, respectively.

**Step 5.** Judge whether the limit condition exsits

There is no limit condition in this case study.

**Step 6.** Modify the multipliers of PSFs

We use Eq. (9) to modify the multiplier for each PSF. The modified multipliers of PSFs for Diagnosis portion are shown in Table 9, and the modified multipliers of PSFs for Action portion are shown in Table 10.

As can be seen from Tables 8 and 9, the modified PSF multipliers are similar to the original PSF multipliers (assigned based on the experts' opinion). There are two reasons for the similarity between the modified PSF multiplier and the original PSF multiplier. One is that the original PSF multiplier equals 1, which means the PSF has no adjustment on the calculation of HEP. According to Eq. (9), the modified PSF multiplier equals 1 as well. This is reasonable since no matter how important the PSF is, the PSF multiplier "1" will not produce an effect on the calculation of HEP. The second one is that the relative weight of the PSF is close to 1, which means the PSF is important and can provide more independent information. When the weight of the PSF equals 1, according to Eq. (9), the modified PSF multiplier equals the original PSF multiplier, which means the effect of the PSF on the calculation of HEP is not discounted. In Tables 8 and 9, most of the original PSF multipliers are assigned 1, and the weights of other PSFs are close to 1. Thus, the modified PSF multipliers are similar to those of experts. If the original multiplier changes, the modified multiplier will be different.

**Step 7.** Calculate HEP

According to Eq. (1), the HEP in the diagnosis stage is 0.047673, the HEP in the action stage is 0.001238, and thus the final HEP is 0.048911. The final HEP obtained by traditional SPAR-H method is

**Table 3**
The relative relationships among SPAR-H PSFs [20].

| Influence of X upon Y | Available Time (X1) | Stress/ Stressors(X2) | Complexity(X3) | Experience/Training (X4) | Procedures (X5) | Ergonomics/HSI (X6) | Fitness for duty (X7) | Work Processes(X8) |
|---|---|---|---|---|---|---|---|---|
| Available Time(Y1) | 1.0 | Medium to high | Medium to high | Medium | Medium to high | Medium | Low to medium | Low to moderate |
| Stress/Stressors(Y2) | High | 1.0 | Medium to high | Medium | Low to medium | Low to medium | Low | Low |
| Complexity(Y3) | Medium to high | High | 1.0 | Medium to high | Medium | Medium | Medium | Medium |
| Experience/Training (X4) | Low | Medium | Low | 1.0 | Low | Low | Low | Low |
| Procedures(Y5) | Low | Low | Medium | Low | 1.0 | Low | Low | Medium |
| Ergonomics/Human-System Interface(HSI)(Y6) | Low | Low | Low to medium | Low | Low | 1.0 | Low | Low |
| Fitness for duty(Y7) | Low | Medium to high | Medium | Low | Low | Low | 1.0 | Low to medium |
| Work Processes(Y8) | Medium | Medium | Medium | Medium | Medium | Low | Low to medium | 1.0 |

• Note: source from Ref. [30], Appendix G, Table G-1.

**Table 4**
Inputs relative relationships for DEMATEL.

| Influence of Y upon X | Available Time(X1) | Stress/ Stressors(X2) | Complexity(X3) | Experience/Training (X4) | Procedures(X5) | Ergonomics/HSI (X6) | Fitness for duty(X7) | Work Processes(X8) |
|---|---|---|---|---|---|---|---|---|
| Available Time(Y1) | 1.0 | High | Medium to high | Low | Low | Low | Low | Medium |
| Stress/Stressors(Y2) | Medium to high | 1.0 | High | Medium | Low | Low | Medium to high | Medium |
| Complexity(Y3) | Medium to high | Medium to high | 1.0 | Low | Medium | Low to medium | Medium | Medium |
| Experience/Training (X4) | Medium | Medium | Medium to high | 1.0 | Low | Low | Low | Medium |
| Procedures(Y5) | Medium to high | Low to medium | Medium | Low | 1.0 | Low | Low | Medium |
| Ergonomics/HSI(Y6) | Medium | Low to medium | Medium | Low | Low | 1.0 | Low | Low |
| Fitness for duty(Y7) | Low to medium | Low | Medium | Low | Low | Low | 1.0 | Low to medium |
| Work Processes(Y8) | Low to moderate | Low | Medium | Low | Medium | Low | Low to medium | 1.0 |

**Table 5**
Direct relation matrix.

| | Available Time | Stress/Stressors | Complexity | Experience/Training | Procedure | Ergonomics/HSI | Fitness for duty | Work Process |
|---|---|---|---|---|---|---|---|---|
| Available Time | 0 | 9 | 7 | 1 | 1 | 1 | 1 | 5 |
| Stress/Stressors | 7 | 0 | 9 | 5 | 1 | 1 | 7 | 5 |
| Complexity | 7 | 7 | 0 | 1 | 5 | 3 | 5 | 5 |
| Experience/Training | 5 | 5 | 7 | 0 | 1 | 1 | 1 | 5 |
| Procedure | 7 | 3 | 5 | 1 | 0 | 1 | 1 | 5 |
| Ergonomics/HSI | 5 | 3 | 5 | 1 | 1 | 0 | 1 | 1 |
| Fitness forduty | 3 | 1 | 5 | 1 | 1 | 1 | 0 | 3 |
| Work Process | 3 | 1 | 5 | 1 | 5 | 1 | 3 | 0 |

**Table 6**
The result of relative weights of PSFs.

| $PSF_i$ | $R_i$ | $C_i$ | $R_i$-$C_i$ | modified vaule($O_i$) | weight($w_i$) |
|---|---|---|---|---|---|
| 1 | 2.8256 | 3.6720 | −0.8464 | 6.0084 | 0.7176 |
| 2 | 3.5465 | 3.1823 | 0.3641 | 7.2189 | 0.8621 |
| 3 | 3.3279 | 4.1931 | −0.8652 | 5.9896 | 0.7153 |
| 4 | 2.7456 | 1.2269 | 1.5187 | 8.3734 | 1.0000 |
| 5 | 2.4651 | 1.7905 | 0.6746 | 7.5293 | 0.8992 |
| 6 | 1.9207 | 1.0507 | 0.8700 | 7.7248 | 0.9225 |
| 7 | 1.6215 | 2.2619 | −0.6404 | 6.2144 | 0.7422 |
| 8 | 1.9863 | 3.0617 | −1.0755 | 5.7793 | 0.6902 |

**Table 8**
Evaluating PSFs for the action portion.

| $PSF_i$ | PSFs | PSF Levels | Multiplier for Action($\alpha_i^A$) |
|---|---|---|---|
| 1 | Available Time | Nominal time | 1 |
| 2 | Stress/Stressors | Nominal | 1 |
| 3 | Complexity | Nominal | 1 |
| 4 | Experience/Training | High | 0.5 |
| 5 | Procedure | Available,but poor | 5 |
| 6 | Ergonomics/HMI | Good | 0.5 |
| 7 | Fitness for duty | Nominal | 1 |
| 8 | Work Process | Nominal | 1 |

**Table 7**
Evaluating PSFs for the diagnosis portion.

| $PSF_i$ | PSFs | PSF Levels | Multiplier for Diagnosis($\alpha_i^D$) |
|---|---|---|---|
| 1 | Available Time | Nominal time | 1 |
| 2 | Stress/Stressors | High | 2 |
| 3 | Complexity | Nominal | 1 |
| 4 | Experience/Training | High | 0.5 |
| 5 | Procedure | Diagnostic/symptom oriented | 0.5 |
| 6 | Ergonomics/HMI | Poor | 10 |
| 7 | Fitness for duty | Nominal | 1 |
| 8 | Work Process | Nominal | 1 |

0.05125 [20], which is larger than the result of the proposed method. The reason for the difference lies in the modification of the PSF multipliers.

### *4.2. Additional cases*

In order to illustrate the superiority of the proposed method, additional cases are designed in this section to calculate the final HEP using the classical SPAR-H method and the proposed method when the PSF multipliers are all greater than 1 (negtive) and less than or equal to 1(positive), respectively, and to make a comparison.

**Case1.** When all PSFs influences are negative, according to Table 1,

**Table 9**
Modified multipliers of PSFs for Diagnosis portion.

| $PSF_i$ | Multiplier for Diagnosis($\alpha_i^D$) | weight($w_i$) | Modified multiplier for Diagnosis($\alpha_i^{D*}$) |
|---|---|---|---|
| 1 | 1 | 0.7176 | 1 |
| 2 | 2 | 0.8621 | 1.8621 |
| 3 | 1 | 0.7153 | 1 |
| 4 | 0.5 | 1.0000 | 0.5 |
| 5 | 0.5 | 0.8992 | 0.5504 |
| 6 | 10 | 0.9225 | 9.3028 |
| 7 | 1 | 0.7422 | 1 |
| 8 | 1 | 0.6902 | 1 |

**Table 10**
Modified multipliers of PSFs for Action portion.

| $PSF_i$ | Multiplier for Action($\alpha_i^A$) | weight($w_i$) | Modified multiplier for Action($\alpha_i^{A*}$) |
|---|---|---|---|
| 1 | 1 | 0.7176 | 1 |
| 2 | 1 | 0.8621 | 1 |
| 3 | 1 | 0.7153 | 1 |
| 4 | 0.5 | 1.0000 | 0.5 |
| 5 | 5 | 0.8992 | 4.5968 |
| 6 | 0.5 | 0.9225 | 0.5387 |
| 7 | 1 | 0.7422 | 1 |
| 8 | 1 | 0.6902 | 1 |

we assume the PSF levels and multipliers of SPAR-H as shown in Table 11.

**Case2.** When all PSFs influences are positive, according to Table 1, we assume the PSF levels and multipliers of SPAR-H as shown in Table 12.

When all multipliers are greater than 1, based on Table 11, the HEP of the diagnosis part and the action part of the classical SPAR-H method can be calculated as 0.9995 and 0.9934. Respectively, according to Eq. (2). When the multipliers are all less than or equal to 1, based on Table 12, according to Eq. (1), they can be calculated as 0.000010 and 0.000013. Accordingly, the HEP of the proposed method can also be calculated, and the final result is shown in Table 13. It should be noted that the number of decimal digits does not reflect the accuracy of the result, but is used for better comparison and higher level of traceability.

**Table 13**
Comparison of the results.

| HEP | Case1 (Multipliers > 1) | | Case2 (Multipliers≤1) | |
|---|---|---|---|---|
| | SPAR-H | Proposed method | SPAR-H | Proposed method |
| Diagnosis | 0.9995 | 0.9986 | 0.000010 | 0.000161 |
| Action | 0.9934 | 0.9786 | 0.000013 | 0.000062 |

According to Table 13, when the multipliers of PSFs are all greater than 1, each PSF plays a negative role. As the dependencies between PSFs are not considered in the classical SPAR-H, the related part is repeatedly calculated, which will make the final HEP become greater than the actual one. The method proposed in this paper takes the dependencies into account and reduces the double counting of the related part, resulting in the reduction of final HEP.

**Table 11**
Multipliers of the negative PSFs (Multipliers > 1).

| PSFs | weight($w_i$) | Multiplier for Diagnosis($\alpha_i^D$) | Modified multiplier for Diagnosis($\alpha_i^{D*}$) | Multiplier for Action($\alpha_i^A$) | Modified multiplier for Action($\alpha_i^{A*}$) |
|---|---|---|---|---|---|
| 1 | 0.7176 | 10 | 7.4580 | 10 | 7.4580 |
| 2 | 0.8621 | 2 | 1.8621 | 2 | 1.8621 |
| 3 | 0.7153 | 2 | 1.7153 | 2 | 1.7153 |
| 4 | 1.0000 | 10 | 10 | 3 | 3 |
| 5 | 0.8992 | 5 | 4.5968 | 5 | 4.5968 |
| 6 | 0.9225 | 10 | 9.3028 | 10 | 9.3028 |
| 7 | 0.7422 | 5 | 3.9686 | 5 | 3.9686 |
| 8 | 0.6902 | 2 | 1.6902 | 5 | 3.7608 |

**Table 12**
Multipliers of the positive PSFs (Multipliers ≤1).

| PSFs | weight($w_i$) | Multiplier for Diagnosis($\alpha_i^D$) | Modified multiplier for Diagnosis($\alpha_i^{D*}$) | Multiplier for Action($\alpha_i^A$) | Modified multiplier for Action($\alpha_i^{A*}$) |
|---|---|---|---|---|---|
| 1 | 0.7176 | 0.1 | 0.3542 | 0.1 | 0.3542 |
| 2 | 0.8621 | 1 | 1 | 1 | 1 |
| 3 | 0.7153 | 0.1 | 0.3562 | 1 | 1 |
| 4 | 1.0000 | 0.5 | 0.5 | 0.5 | 0.5 |
| 5 | 0.8992 | 0.5 | 0.5504 | 1 | 1 |
| 6 | 0.9225 | 0.5 | 0.5387 | 0.5 | 0.5387 |
| 7 | 0.7422 | 1 | 1 | 1 | 1 |
| 8 | 0.6902 | 0.8 | 0.8620 | 0.5 | 0.6549 |

Moreover, when the multipliers of PSFs are all less than or equal to 1, each PSF plays a possitive role. As the dependencies between PSFs are not considered in the classical SPAR-H, the final HEP will be less than the actual one due to repeated calculation of the related part. The results of the proposed method are more reasonable.

## 5. Conclusion

In the SPAR-H method, the PSFs are treated independently, which could make the calculated HEPs either too conservative or too optimistic. In this paper, a new method is proposed to handle the dependences among PSFs in SPAR-H to obtain more reasonable results. The contributions of the paper are: provide an effective method for modeling the dependences among PSFs; provide an applicable method for calculating HEPs which considers the dependences among PSFs.

The proposed method consisted of three main procedures. Firstly, the dependences among PSFs are analyzed by using DEMATEL method. Secondly, PSFS are assigned different weights according to their dependent relationships (PSFs with higher values of R−C have larger weights). Thirdly, multipliers of PSFs are modified based on the relative weights of PSFs (the larger the weights, the less the corresponding original multipliers are discounted). Finally, a case study is illustrated to show the use of the proposed method. Moreover, two additional cases are designed and analyzed to show the effectiveness of the proposed method. The duplicate calculations of the dependent part can be reduced and the results are more reasonable.

In the future, research efforts are needed to address the uncertainty associated with the assignment of PSF multipliers. Also, the decision support methods for combining evaluations of PSF levels from different experts (especially contradictory evaluations) should be further investigated.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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