CHEMICAL ENGINEERING TRANSACTIONS

VOL. 90, 2022

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Aleš Bernatík, Bruno Fabiano
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ISBN 978-88-95608-88-4;; **ISSN** 2283-9216

DOI: 10.3303/CET2290119

A Risk-Based Grey Relational Analysis for Identifying Key Performance Shaping Factors to Promote the Management for Human Reliability during Shipping LNG Offloading

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This study aims to propose an approach for determining key Performance Shaping Factors (PSFs) to promote human reliability management during LNG ship offloading process. Offloading LNG from ship to onshore terminal is a high-risk and human-related operation; a small human error may trigger catastrophic consequences such as fire, explosion, and even fatality. Therefore, ensuring high human reliability level is necessary. It is widely acknowledged that human reliability is mainly influenced by plenty of PSFs. If some top important PSFs can be identified, then it will be helpful to human reliability assurance and targeted management for avoiding human errors in the shipping LNG offloading work. Determining key PSFs is a decision-making system, but there is always lack of historical data of PSF. Namely, this decision-making system has strong characteristic of grey, which is an obstacle for finding the significant PSFs. Due to this condition, the grey theory-based Grey Relational Analysis (GRA) method is a choice and should be selected for handling the insufficient PSF data and grey characteristics. Apart from GRA, the definition of risk (frequency products consequence) is utilised as the basis for reasonably explaining the ranking order of each involved PSF. In one word, GRA is firstly conducted from the view of frequency and the view of consequence, then combining the results together to identify key PSFs. The proposed method is applied to a real shipping LNG offloading case. The final result indicates that the proposed method provides a reasonable and effective way to find key PSFs for ensuring human reliability in shipping LNG offloading work.

1. Introduction

According to the historical recording, shipping LNG offloading process is a high-risk task (Zhang and Tan, 2018). During this work, a small operational deviation may lead to fire, explosion, and even fatality, so human reliability is a crucial role in ensuring offloading safety. Fortunately, the significance of human reliability has gradually been acknowledged by many safety-related industries including the process industries, the oil and gas industries, and the offshore industries (Liu and Li, 2014; Zhang and Tan, 2018). So far, many Human Reliability Analysis (HRA) methods have been designed, and among those methods, PSFs or some similar subjects are necessary to assess the human reliability performance and human error probability (Liu et al. 2017). Given that, it is meaningful to identify several key PSFs for targeted human reliability management in the shipping LNG offloading process. However, the performance data of each PSF is always very insufficient for use, which is an obstacle for people to find the key PSFs. Besides, as the data is limited, the standard for ranking and finding key PSFs is always subjective. In order to effectively determine several important PSFs for human reliability management in shipping LNG offloading work, the issues mentioned above should be considered.
Facing the problems, grey theory is a reasonable choice to address the issue caused by limited PSF data. Grey theory is particularly designed for the system with incomplete information (Deng, 1982), and many grey theory-based methods have been designed for addressing decision making problem (Zhou and Thai, 2016). Among them, the Grey Relational Analysis (GRA) is a famous one. This method uses geometric similarity to decide the important attribute in a system. So far, GRA has been combined with Failure Mode and Effects Analysis (FMEA) to identify safety-critical failure modes for the equipment at ship, medical device, and stream turbine at power

Paper Received: 18 January 2022; Revised: 26 March 2022; Accepted: 18 April 2022
Please cite this article as: Ge J., Zhang R., Wu S., Xu N., Du Y., 2022, A Risk-Based Grey Relational Analysis for Identifying Key Performance Shaping Factors to Promote the Management for Human Reliability during Shipping LNG Offloading, Chemical Engineering Transactions, 90, 709-714 DOI:10.3303/CET2290119

plants (Song et al., 2020; Chen and Deng, 2018; Li and Chen, 2017; Zhou and Thai, 2016). Therefore, considering our study, GRA should be a useful selection to deal with poor PSF data.

Apart from the data problem, we also need to rank and find significant PSFs in a rational way so that to decrease the subjective level in determining key PSFs for human reliability management in shipping LNG offloading. The definition of risk (frequency products consequence) is an option for reasonably ranking and finding key PSFs, and it has been used for evaluating the importance of PSFs for the operations at main control rooms in nuclear power plants (Liu et al., 2017). According to the previous description, GRA has been successfully combined with FMEA, so to this study, we can combine GRA with the definition of risk to overcome the limitation of incomplete PSF data and to rationally evaluate each PSF from two dimensions (one is frequency, the other is consequence).

The proposed method is tested at the Beihai LNG Terminal of China to identify some key PSFs for targeted human reliability management during LNG ship offloading. The PSFs used in this study come from the well-known HRA method “Cognitive Reliability and Error Analysis Method (CREAM)”, because it has been practised in many safety-related applications (Zhou et al., 2017; Ung, 2018; Zhang et al., 2021). The remainder of this paper is arranged as follow. Section two explains the method used in this study. Section three applies the proposed method for LNG offloading at the selected LNG Terminal. Section four gives a discussion for the proposed method. Finally, a conclusion is given in Section five.

2. Style guidelines

Based on the objective of this study, the main approach is the combination of GRA with “risk”. The procedures and the details of the proposed method are presented at the following parts.

2.1 The procedure of the proposed method

The proposed method starts with a data collection. As data is insufficient, this step is conducted by five experienced and charted experts, and the data of each PSF is respectively evaluated from the aspect of frequency and consequence. Then, the second step is the GRA process. In this step, GRA is applied to the collected data from the five invited experts, and GRA is also conducted from the view of frequency and consequence. In the second step, the frequency-related grey degree of each PSF and the consequence-related grey degree of each PSF for shipping LNG offloading work can be determined. The third step is based on the definition of “risk” and the product rule to multiply the frequency-related grey degree and the consequence-related grey degree to finally decide each PSF’s grey relational degree. The last step is according to the final grey degrees to identify key PSFs and to suggest some targeted human reliability management plans for shipping LNG safe offloading work. Figure 1 illustrates the flow of the proposed method by this study.

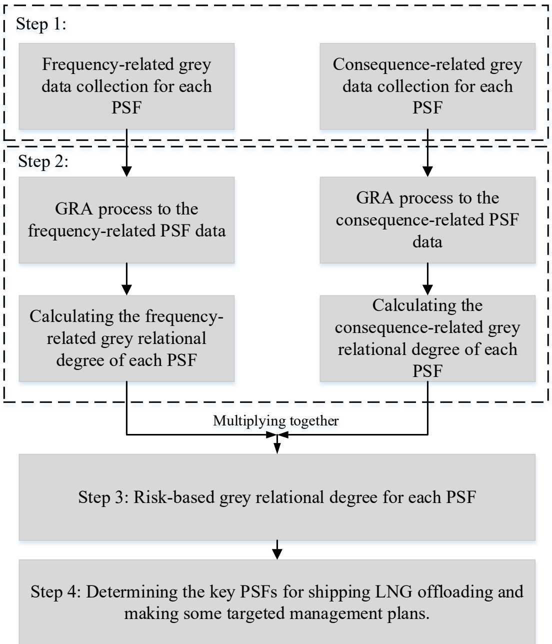

Figure 1: The procedure of the proposed method

2.2 The details of the proposed methodology

GRA and "risk" are the main parts of the proposed method, so they are illustrated in this section. GRA starts with the grey data collection work; then, those collected data can be represented by a grey matrix which is presented as Eq(1).

$$\boldsymbol{T}_G = \begin{pmatrix} T_1(1) & T_1(2) & \cdots & T_1(n) \\ T_2(1) & T_2(2) & \cdots & T_2(n) \\ \vdots & \vdots & & \vdots \\ T_m(1) & T_m(2) & \cdots & T_m(n) \end{pmatrix} \tag{1}$$

where $\boldsymbol{T}_G$ is grey matrix; $T_m(n)$ means the element for the *n*th criteria in the data series of the *m*th attribute. With the grey matrix, the next step is to decide the reference series and each comparative series. Generally speaking, the reference series is the set of the maximum or minimum data of each row in Eq(1). This study selects the maximum data, and Eq(2) presents the general expression for the reference series. The comparative series is same with each row in Eq(1).

$$\boldsymbol{T}_O = (T_{O1}, T_{O2}, \cdots, T_{On}) \tag{2}$$

where $\boldsymbol{T}_O$ is the reference series; T_{On} is the maximum data in the *n*th criteria (the nth column in the grey matrix). Afterwards, the grey relational coefficient between each element in reference series and each element in comparative series can be calculated by Eq(3).

$$g_k^j = \frac{min(min|\boldsymbol{T}_O - \boldsymbol{T}_C|) + max\ (max|\boldsymbol{T}_O - \boldsymbol{T}_C|)}{\left|T_{Ok} - T_{Ck}^j\right| + \delta \times max\ (max|\boldsymbol{T}_O - \boldsymbol{T}_C|)} \tag{3}$$

where the terms $min(min|\boldsymbol{T}_O - \boldsymbol{T}_C|)$ and $max(max|\boldsymbol{T}_O - \boldsymbol{T}_C|)$ represent the minimum difference and the maximum difference between the reference series and all comparative series; $T_{Ok}$is the *k*th element in reference series, and $(1 \leq k \leq n)$; T_{CK}^j is the kth element in the comparative series for the *j*th attribute, and $(1 \leq j \leq m)$; g_k^j is the grey relation coefficient between the kth element in the reference series and that in the comparative series for the *j*th attribute; $\delta \in [0,1]$ is the identifier, and generally $\delta = 0.5$ (Zhou and Thai, 2016). With the grey relational coefficient, the grey relational degree can be determined by Eq(4).

$$g_j = \frac{1}{n} \sum_{k=1}^{n} g_k^j \tag{4}$$

where g_j is the grey relational degree of the *j*th attribute.

Since this study takes the definition of risk as the standard to assess and to find key PSFs, with the results collected from Eq(4), the final grey degree for each attribute is calculated through Eq(5). Namely, through production rule to combine the frequency-based grey relational degrees and the consequence-based grey relational degrees together.

$$g_j^{Risk.} = g_j^{Fre.} * g_j^{Con.} \tag{5}$$

where, $g_j^{Risk.}$ is the final risk-based grey relational degree for the *j*th attribute; $g_j^{Frs.}$ and $g_j^{Con.}$ respectively represent the frequency-based grey relational degree and the consequence-based grey relational degree of the *j*th attribute. Finally, the key PSFs for shipping LNG work can be determined, and the management team can make some targeted plans to improve human reliability and to defend human errors.

3. Case study

The shipping LNG offloading process in the Beihai LNG Terminal of China is selected as the engineering case to validate the proposed method. As human error is a considerable factor that threatens the LNG offloading safety, it is necessary to find out several top important PSFs for targeted management to ensure human reliability during the offloading process. The nine common performance conditions in CREAM method are selected as the nine PSFs. The nine PSFs provided by professor Hollnagel (1998) are:

- Adequacy of organization,
- Working condition,
- Adequacy of man-machine inference and operational support,
- Availability of procedures/plans,
- Number of simultaneous goals,

- Available time,
- Time of day,
- Adequacy of training and expertise,
- Crew collaboration quality.

According to the procedure shown in Figure 1, five experienced and charted experts are invited to evaluate the grey data. Those five invited experts are all licensed with at least 10 years working experience in shipping LNG-related domain. Besides, in order to ensure the consistency of the evaluation, a “zero to five scale” is used to express the frequency level and consequence level of each PSF. Table 1 shows the scale as well as the definition of each scale for frequency level and for consequence level.

Table 1: The scale of the frequency level and the consequence level

Scale	Frequency level	Consequence level
[0,1)	Low frequency	Low consequence
[1,2)	Moderate low frequency	Moderate low consequence
[2,3)	Middle frequency	Middle consequence
[3,4)	Moderate high frequency	Moderate high consequence
[4,5]	High frequency	High consequence

Table 2: The evaluation scores of frequency level for the nine PSFs

No.	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
PSF1	1.0	1.8	1.2	1.5	1.5
PSF2	3.3	3.8	3.0	3.5	3.8
PSF3	3.8	4.2	4.0	4.0	4.0
PSF4	1.5	1.2	1.5	1.3	1.2
PSF5	2.5	2.3	2.0	2.8	2.5
PSF6	2.0	1.8	2.3	2.0	2.0
PSF7	2.0	1.6	2.0	2.5	2.0
PSF8	1.0	1.0	1.2	1.0	1.0
PSF9	1.5	1.6	1.8	1.5	1.5

Table 3: The evaluation scores of consequence level for the nine PSFs

No.	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
PSF1	1.8	2.0	2.0	2.5	2.0
PSF2	2.4	3.0	2.8	2.5	2.8
PSF3	2.3	3.0	2.5	2.5	2.5
PSF4	4.0	3.8	4.0	4.0	4.0
PSF5	2.8	2.0	2.5	3.0	3.2
PSF6	2.0	2.5	2.2	3.0	2.2
PSF7	1.8	1.5	1.5	1.0	1.5
PSF8	4.5	4.0	4.2	4.0	4.2
PSF9	3.2	3.0	3.0	3.5	3.8

Table 4: the grey degree of frequency and consequence for each PSF

PSF	Grey relational degree of each PSF’s frequency	Grey relational degree of each PSF’s consequence
PSF1	0.3816	0.4193
PSF2	0.7656	0.5102
PSF3	1.0000	0.4886
PSF4	0.3768	0.8794
PSF5	0.5082	0.5132
PSF6	0.4489	0.4664
PSF7	0.4513	0.3560
PSF8	0.3513	1.0000
PSF9	0.3985	0.6461

With the scale and the definitions, the PSF are evaluated by the five highly experienced experts. Table 2 and Table 3 presents the evaluated score for each PSF. Based on GRA, each data in Table 2 and Table 3 can be viewed as each element in the grey matrix for PSF's frequency and for PSF's consequence. Namely, Table 2 and Table 3 can be directly expressed by Eq(1). Then, through Eq(2), Eq(3), and Eq(4), the grey relational degree of each PSF's frequency and the grey relational degree of each PSF's consequence can be determined. Their results are displayed in Table 4.
As this study aims to provide a risk-based GRA to identify key PSFs in shipping LNG offloading process, based on the data in Table 4, the final grey relational degree of each PSF can be calculated by Eq(5). Table 5 shows those final results and their corresponding rankings.

Table 5: The comprehensive grey degree of each PSF

PSF	Final grey relational degree	Rank
PSF1	0.1600	Ninth
PSF2	0.3906	Second
PSF3	0.4886	First
PSF4	0.3314	Fourth
PSF5	0.2608	Fifth
PSF6	0.2094	Seventh
PSF7	0.1607	Eighth
PSF8	0.3513	Third
PSF9	0.2575	Sixth

Shown in Table 5, several top-ranking PSFs are identified. Among them, the top three PSFs are PSF3 "Adequacy of man-machine inference and operational support" (0.4886), PSF2 "Working condition" (0.3906), and PSF8 "Adequacy of training and expertise" (0.3513). Then, the leadership and management team in the Beihai LNG Terminal can make some targeted measures to promote human reliability level for avoiding human errors. Some examples of the measures are listed as follows:

- Through in-depth investigation to change some crucial unfriendly designs in the man-machine interface system/facility at the LNG terminal.
- By providing more bonus and investing more money on operators' wellbeing such as comfortable common room and accommodation to make them feel happy with the job.
- Providing more periodically training to make sure people working there can maintain high level of operation performance.

4. Discussion

This study displays an optional passage to identify key PSFs for targeted human reliability management during the selected LNG ship offloading work. The proposed method in this study selects GRA to deal with issue that there is very limited data recording for each PSF, and the definition of risk is utilized as the standard for rationally ranking and deciding important PSFs. Those together form the contribution of this study. If only based on the definition of risk and using the same data in Table 2 and Table 3, the top two ranking PSFs are same with the result from the proposed method, but the results for the third ranking PSF are different. This difference may be caused by the different theory for finding the key PSFs. GRA is based on the geometric similarity, but "risk" is just the products of frequency data and consequence data. As there is always very limited in PSF data recording, we deem it is better to use the proposed method in this study to identify some key PSFs for the targeted management to ensure human reliability in the shipping LNG operation.

5. Conclusions

This paper indicates that the proposed method is functional in finding the key PSFs to ensure human reliability for shipping LNG safe offloading. Through this proposed approach, the significant PSFs for ensuring human reliability during the LNG ship offloading process in the Beihai LNG Terminal can be determined. The top three PSFs are PSF3, PSF2, and PSF8. Then based on such results, the executive team in this terminal can have better decision-making for targeted human error prevention. However, as discussed above, the suggested method needs improvements. The dynamic scenarios of the offloading task should be considered, and the importance weight of each expert should also be involved. More importantly, the recording work for PSF data during some safety and human-related work should be conducted, so in future we can have enough data to create high quality results.

Nomenclature

g_j – grey relational degree of the *j*th attribute, -

$g_j^{Con.}$ – consequence-based grey relational degree of the *j*th attribute, -

$g_j^{Frs.}$ – frequency-based grey relational degree for the *j*th attribute, -

$g_j^{Risk.}$ – risk-based grey relational degree for the *j*th attribute, -

g_k^j - grey relation coefficient between the kth element in the reference series and that in the comparative series for the *j*th attribute, -

$\boldsymbol{T}_C$ – comparative series, -

T_{CK}^j – the kth element in the comparative series for the *j*th attribute, -

$\boldsymbol{T}_G$ – grey matrix, -

$T_m(n)$ – element for the *n*th criteria in the data series of the *m*th attribute, -

$\boldsymbol{T}_O$ – reference series, -

T_{Ok} – the *k*th element in reference series, -

T_{On} – the maximum data in the *n*th criteria, -

δ – identifier, -

Acknowledgments

This study is supported by the University Research Training (URT) project of the Beijing Institute of Petrochemical Technology (Project No. 2021J00176) and Beijing Municipal Natural Science Foundation (Project No. 2214071). Besides, the authors would like to express sincere gratitude for the support and contribution from the Beihai LNG Terminal.

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