Received: 8 December 2020 | Revised: 26 April 2021 | Accepted: 30 April 2021

DOI: 10.1002/prs.12260

ORIGINAL ARTICLE

This document is the accepted manuscript version of the following article: Kyriakidis, M., & Dang, V. N. (2021). A scoping method for human performance integrity and reliability assessment in process industries. Process Safety Progress, 40(4), 224-233. https://doi.org/10.1002/prs.12260

PROCESS SAFETY PROGRESS

# A scoping method for human performance integrity and reliability assessment in process industries

**Miltos Kyriakidis** | **Vinh N. Dang**

Laboratory for Energy Systems Analysis, Paul Scherrer Institute, Villigen PSI, Switzerland

**Correspondence**
Miltos Kyriakidis, Laboratory for Energy Systems Analysis, Paul Scherrer Institute, Villigen PSI, Switzerland.
Email: miltiadis.kyriakidis@psi.ch

## Abstract

An approach to manage human performance related risks in petrochemical sector is to use human reliability analyses (HRA) techniques. However, the focus of HRAs on individuals and on decomposed tasks overlooks the likelihood that collective actions and behaviors might lead to system failures. This study introduces an alternative approach, referred to as Human Performance Integrity (HPI) index, to assess human performance conditions on the whole, as they relate to safety, in petrochemical facilities. Additionally, the approach is used to rate installations in terms of their defenses against safety-relevant human failures. The HPI index is built upon the notions of Cognitive Reliability and Error Analysis Method. By means of a 42-question survey, data was collected on the factors that improve or reduce human performance in 11 oil refineries. Data was used to assess the facilities' safety performance. Results were compared against information obtained from relevant investigation reports, as well as and an independent evaluation of the facilities carried out by certified auditors. Findings support the use of HPI index from novice and experienced scholars and/or practitioners as a quick and effortless, yet sound and efficient manner to assess safety and reliability performance of oil refineries from a human factors perspective.

**KEYWORDS**
CREAM, expert judgment, human performance integrity, oil refineries, questionnaire survey, safety assessment

## 1 | INTRODUCTION

Investigations of accidents in complex socio-technical systems worldwide show that technical, human, operational, and organizational factors influence largely the accident sequences.[1] In process industries quantitative risk analyses have focused mostly on the technical aspects of systems safety, overlooking the corresponding human and organizational facets that contribute to the overall system risk.[2,3]

Today, approximately 700 oil refineries exist all over the world.[4] Their processes and operations pose several safety and environmental concerns inherent to their features–working with flammable and toxic fluids,[3] while the available data for assessing the status of chemical accident risk globally is very limited.[5] Bellamy,[6] as early as 1994, has discussed and highlighted the influence of human factors on safety in chemical, offshore, installations. Yet, recent statistics indicate that more than 80% percent of accidents in the sector are attributed to human and organizational related failures,[7] with 70% of them to occur while facilities are operating under normal conditions.[8]

Traditionally, an approach to manage risks related to human operational failures is to use Human Reliability Analysis (HRA) techniques with the aim to identify, model and finally quantify human failure events.[9,10] Despite developments in HRA for the process industry (e.g.,[1,2,7,11,12,13]) not only is research on how to apply HRA to the sector limited,[14] but there is also no consensus on a globally accepted requirement for quantitative risk assessment within the industry.[15] To this end, an alternative approach is to evaluate human performance conditions on the whole, as they relate to safety. This measure, hereafter will be referred to as Human Performance Integrity (HPI) index, has a twofold purpose. First, to assess human performance, and in turn reliability, with respect to safety, based on a set of pre-selected Performance Shaping Factors (PSFs) that affect human performance. Second, to rate facilities in terms of their defenses against safety-relevant human failures. The suggested approach is at an overview level, instead of the more granular level of prior work. Therefore, we argue that it can provide useful insights to the risk management cycle as a whole. In other words, the HPI index can be viewed as a tool to assess and estimate the safety performance of facilities from a human factors viewpoint. In this paper, the HPI index was used to assess safety performance of oil refineries.

The HPI index is neither an attempt to create a new HRA technique nor to improve an existing one. Nonetheless, it is largely built upon the notion of PSFs. Therefore, it is related to an existing, renowned HRA technique. For its development six steps were followed:

1. Identification, definition and classification of the factors that affect human performance in the process industry,
2. Selection of a suitable HRA technique,
3. Design and construction of the Human Performance Integrity index.
4. Calculation and interpretation of the HPI index, and
5. Confirmation of the HPI index findings.

The remainder of this paper is divided into three sections. Section 2 discusses the underpinning methodology for the development of the HPI index. Section 3 presents the findings derived from the implementation of the HPI index in 11 oil refineries around the world. Finally, Section 4 summarizes the findings, discusses the limitations, and outlines the direction of future work.

## 2 | METHODOLOGY

### 2.1 | Identification of factors–definitions and classification

To determine the factors that influence human performance in oil refineries, first a literature review[16-33] was conducted across a broad range of sectors.

Then, a review was carried out of studies and reports[1,2,7,11-14,31,34-42] focusing on chemical plants and oil refineries. The second review confirmed the findings from the initial review, and identified any missing factors and/or factors not relevant to the scope of the study. Finally, a subject matter experts (SMEs) workshop was conducted to corroborate the findings. Eight engineers participated in the workshop; each engineer had, at the time of the workshop, at least 6 years of experience on the inspection of oil refineries for re-insurance purposes.

Twenty-four factors were in total identified through the three steps process and classified as follows:

- Lighting, noise, room temperature, humidity;
- Stress;
- Age, sleep duration, fitness for duty, shift work, distance from workplace, fatigue;
- Work experience, training;
- Social skills, work satisfaction, leadership-motivation, employees collaboration;
- Decision-making skills
- External support, human machine interface
- Activity planning, operating instructions, production planning, maintenance planning

### 2.2 | HRA method selection

To benefit from existing research and up-to-date developments, the HPI was built upon the notions of an existing renowned HRA technique. Among the several methods in the safety science literature (e.g., [43,44]), here we used Hollnagel's[45] Cognitive Reliability and Error Analysis Method (CREAM).

CREAM identifies nine factors, called CPCs (Common Performance Conditions), that affect human performance and reliability: (i) adequacy of organization, (ii) working conditions, (iii) adequacy of man–machine interface (MMI) and operational support, (iv) availability of procedures and plans, (v) number of simultaneous goals, (vi) available time, (vii) time of day, (viii) adequacy of training and experience, and (viii) crew collaboration quality. The nine CPCs could have a negative, neutral or positive impact on human performance. CREAM also introduces four control modes, which are determined based on the CPCs impact on human performance, aiming at specifying how people are able to maintain control of a situation.[46] The four modes are labeled “scrambled”, “opportunistic”, “tactical” and “strategic”, as shown in Figure 1, and are associated with different reliability intervals representing the probabilities of a human action to fail.[45]

The score for each CPC is obtained by counting the number of times that a CPC is expected to reduce, improve or have no impact on human performance. For a given situation the description of the CPCs will result in a specific value of combined CPC score, expressed as the triplet ($\Sigma_{\text{Reduced}}$, $\Sigma_{\text{Not significant}}$, $\Sigma_{\text{Improved}}$), and the combined scores will determine the coordinates in the control modes axes. The factors that have no impact on human performance are allotted a zero value.

CREAM was selected because it has been broadly applied across industries (e.g., [47,48-51]), it can be easily used both by experts and novice in the field of human performance analysis, and it can provide an accurate sense of reliability. Further, it is a well-structured and systematic approach to error identification and quantification, it can be used both proactively and retrospectively, and it does take into consideration environmental and system causes of error. Finally, CREAM's taxonomy of CPCs includes, directly or indirectly, all the factors that deemed to affect human performance in oil refineries.

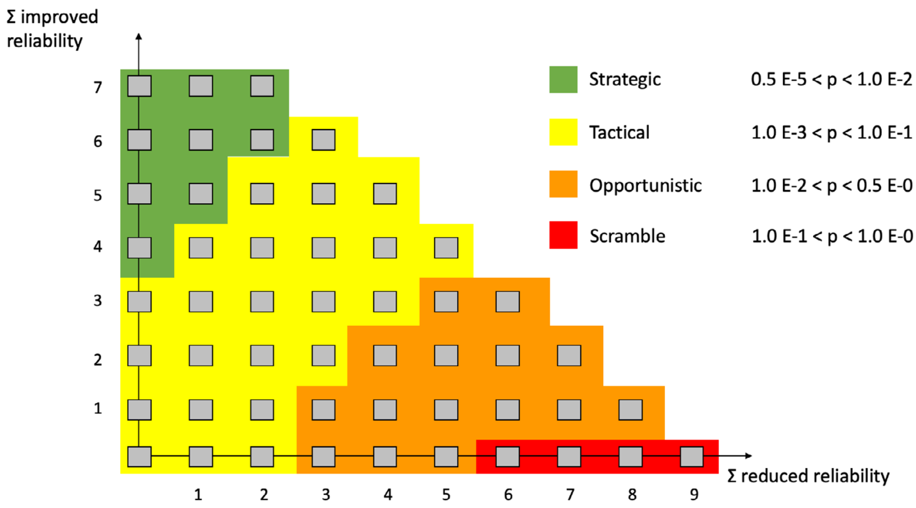



**FIGURE 1** Relations between CPC score and control modes (adopted by [47]) [Color figure can be viewed at wileyonlinelibrary.com]

## 2.3 | Design and construction of the Human Performance Integrity index

To proceed with the development of the HPI index the identified factors presented in Section 2.1 were compared against the categories of CPCs in CREAM and re-classified accordingly, as presented in Table 1.

The factors were assessed with respect to their impact on human performance. To collect the necessary information the authors devised a questionnaire, which can be found in the supplementary material. The questionnaire, referred to as "surveyors" questionnaire, is addressed to safety experts who survey/audit the facilities. It comprises 42 questions, divided and assigned to the nine CREAM categories of CPCs. Two groups of questions are included: the first, encompasses questions that can be answered during a discussion/interview between the surveyor and the employees (Meeting), while the second corresponds to questions answered by the surveyors' sheer assessment of the facility (Assessment). Answers are given in the form of multiple choices; an area for the surveyors to add any other comments is also provided. For each question a grade and weight are assigned, which indicate the importance of the specific question within the CPC category, as described in Section 2.4.

While some of the questions can be relatively easily graded, some others may be considered quite subjective, hence hanging on individual bias. To avoid individual and/or hindsight biases, the surveyors were introduced and trained on how to use and fill in the questionnaire prior to the assessments. At the training session clarifications on the questions, if required, were provided, while a common understanding on how to more objectively answer the questions was established.

**TABLE 1** Analogy between the categories of CPCs in CREAM and the HPI identified factors

| CREAM CPCs | Identified Factors |
|---|---|
| Working conditions | Lighting, noise, temperature, humidity |
| Time of day (Fatigue) | Shift work, sleep duration, age, fit for duty, distance, fatigue |
| Number of simultaneous goals | Stress |
| Available time | Stress |
| Adequacy of training & experience | Work experience, training |
| Crew collaboration quality | Work satisfaction, leadership, social skills, employees vooperation |
| Adequacy of organization | Decision-making skills |
| Adequacy of MMI and operational support | External support, HMI |
| Availability of procedures/plans | Activity planning, operating instructions, production planning, maintenance planning |

## 2.4 | HPI index calculation and interpretation

For the calculation of the HPI index three steps are followed:

1. A principal question is defined for each of the CPC categories, indicating the one question deemed to affect human performance the most.
2. A "weight" (w) is assigned to each of the questions in every CPC category, in a zero to 10 scale. The weight represents the importance of the specific question in the CPC category. The sum weight per category equals 10.
3. A "grade" (g) is allocated to each of the responses, in a zero to 1 scale. The grade displays the importance of an answer to a specific question, regardless of the question's influence on the corresponding CPC category.

To define the principal question in the CPC categories and assign the weights and grades for each of the questions and answers respectively, a review of the literature was conducted (e.g., [52]). Then, a second workshop was carried out with the same eight engineers who were involved in the identification of the factors that affect human performance. Table 2 illustrates a CPC category, its associated questions, and the corresponding weights and grades.

The experts were also asked to define boundaries, in a zero to 10 scale, to describe the influence of CPCs on the performance of the operators. In other words, experts were invited to indicate when a CPC has a positive, negative or neutral impact on human performance. For this, they were instructed to determine the boundaries to assess each of the CPCs, as presented in Table 3. Based on CREAM definitions, the CPCs "Number of Simultaneous Goals" and "Time of Day" cannot result in an improved human performance. This was also adapted in this work. It should also be mentioned here that the values in Table 3 represent a rather conservative viewpoint and require further investigation and possible adjustments.

Table 4 illustrates an example of the CPC "Time of day - Fatigue" calculation, which comprises six questions. The principal question was deemed to be "How many hours is the daily shift (shift work)"; it was assigned a "weight" of five. The surveyors could choose among four possible answers. In this example, operators shift lasts for 12 hours, which is graded with a zero value.

**TABLE 2** Questions regarding the "Adequacy of MMI & Operational Support" CPC

| Adequacy of MMI & Operational Support | |
|---|---|
| (A) What is the adequacy of the equipment | Grade Weight |
| ☐ Good | 1 3 |
| ☐ Sufficient | 0.5 |
| ☐ Poor | 0 |
| (A) What is the maintenance condition of the equipment | Grade Weight |
| | 1 4 |
| ☐ Good | 0.5 |
| ☐ Sufficient | 0 |
| ☐ Poor | |
| (A) Is there an alarm management system (AMS) in the control room | Grade Weight |
| | 1 3 |
| ☐ Yes | 0 |
| ☐ No | |

The contribution of "shift work" to the "Time of Day - Fatigue" category is calculated as follows:

$$\text{Shift work} = \text{grade} \times \text{weight} = 0.5 \times 0 = 0, \tag{1}$$

The total result for the CPC category is then computed, similar to,[52] as

$$Total\,CPC = \sum_{i=1}^{n} w_i \times g_i, \tag{2}$$

In this example, this is:

$$\begin{aligned} Total\,\text{Fatigue} &= \sum_{i=1}^{n} w_i \times g_i \\ &= (1\text{x}0.5) + (0.5\text{x}0) + (5\text{x}0) + (0.5\text{x}1) + (2\text{x}0) + (1\text{x}05) \\ &= 1.5, \end{aligned}$$

To interpret the value, the relation between CPC score and control modes shown in Figure 1 was associated with the boundaries in Table 3. Here, Fatigue = ≤5; thus, it is claimed that it has a negative impact on human performance. Following the same rational the assessment of the facility with respect to human performance was calculated, as illustrated in Figure 2. For a more intuitive mechanism to assess the facilities, in terms of their defenses against safety-relevant human failures, the four control modes of CREAM, i.e.," strategic", "tactical", "opportunistic", and "scrambled" are replaced by the control modes "very good", "good", "poor", and "very poor" respectively.

## 2.5 | Confirmation of HPI index results

Having defined the value of the HPI index the final step in the process is the confirmation of results. The confirmation of results would benefit from comparing our calculations with results from previous studies. However, due to the lack of similar studies no data is currently available to directly compare the HPI index values. Therefore, findings

**TABLE 3** Boundaries to define the impact of a CPC on human performance

| CPC | Boundaries defining impact on performance |
|---|---|
| Working conditions | Improved >8, Not significant 6 < x = < 8, Reduced = < 6 |
| Fatigue–time of day | Not significant >5, Reduced = < 5 |
| Number of simultaneous goals | Not significant >5, Reduced = < 5 |
| Available time | Improved >8, Not significant 6 < x = < 8, Reduced = < 6 |
| Adequacy of training & experience | Improved >8, Not significant 5 < x = < 8, Reduced = < 5 |
| Crew Collaboration quality | Improved >8, Not significant 6 < x = < 8, Reduced = < 6 |
| Adequacy of organization | Improved >7, Not significant 3 < x = < 7, Reduced = < 3 |
| Adequacy of MMI and operational support | Improved >7.5, Not significant 4.5 < x = < 7.5, Reduced = < 4.5 |
| Availability of procedures/plans | Improved =10, Not significant 7 < x = < 10, Reduced = < 7 |

**TABLE 4** Common Performance Conditions Evaluation based on HPI

| Categories/ Questions | Answers | Grade | Weight (sum = 10) | Result | Total CPC Result | Description |
|---|---|---|---|---|---|---|
| Fatigue | | | | | 1.5 | Reduced |
| How much time do employees need for coming to their workplace (M) | 30 minutes to 1 hour | 0.5 | 1 | 0.5 | | |
| What kind of transportation do the employees use (M) | Private | 0 | 0.5 | 0 | | |
| How many hours is the daily shift (shift work) (A) | 12 hours or more | 0 | 5 | 0 | | |
| What is the shift cycle (shift work) (A) | Forward rolling (Day-Evening- Night) | 1 | 0.5 | 0.5 | | |
| How many consecutive night shifts do you usually work (M) | More than 6 | 0 | 2 | 0 | | |
| How many days of rest are given after Night shifts (M) | 2 days | 0.5 | 1 | 0.5 | | |

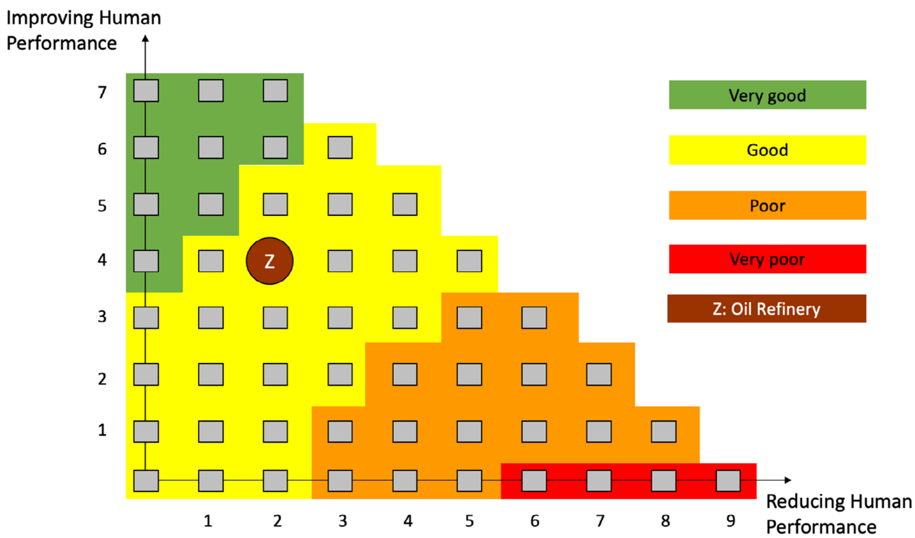



**FIGURE 2** Assessment of a facility "Z" using the Human Performance Integrity index [Color figure can be viewed at wileyonlinelibrary.com]

were compared against information gathered from relevant investigation reports. In this study, four reports were used to confirm the findings. Three of the reports are not publicly available; consequently, neither the analysis nor the discussion of the findings can be detailed in this paper. This is one of the main limitations of this study, which shall be addressed in future work, as mentioned in Section 4.

For the discussion of the results, the publicly available report by the U.S. Chemical Safety and Hazard Investigation Board[36] on the BP Texas City refinery accident is used in this paper. The event occurred in Texas City on February 23rd, 1999 and resulted in 15 fatalities and 180 injuries. A shelter-in-place order required 43,000 people to remain indoors, while properties were damaged as far away as three-quarters of a mile from the refinery. The BP Texas City accident was selected as one of the most serious, well-known and well documented events in the modern history of the industry associated with human and organizational failures. Although hindsight bias may be considered to have affected the answers to some of the questions, we trust that this is not the case in our study. The questionnaire was devised without prior knowledge of the BP report, while the questions were answered predominantly based on information included in the report. When information was not available, the more conservative answer was chosen. The assessment of the BP facility is included in the supplementary material.

The HPI index results were also verified against findings included in internal reports of a re-insurance company. While it is acknowledged that the performed process to confirm our findings may not be optimal, it can be claimed that overall findings support the use of the HPI index in the process industry to assess human performance and reliability with respect to safety, as well as to rate installations in terms of their protective measures against safety relevant human failures.

## 3 | IMPLEMENTATION OF THE HPI INDEX AND PRELIMINARY FINDINGS

The "surveyors" questionnaire was applied to 11 oil refineries during an auditing process for insurance purposes. The facilities are located as follows: four installations in Europe (A, D, E, F); two in the U.S.A. (J, K); and one in the Middle East (B), India (C), Chile (G); Australia (I); and Canada (H). The findings from the implementation of the questionnaire for the 11 facilities were compared against the results derived

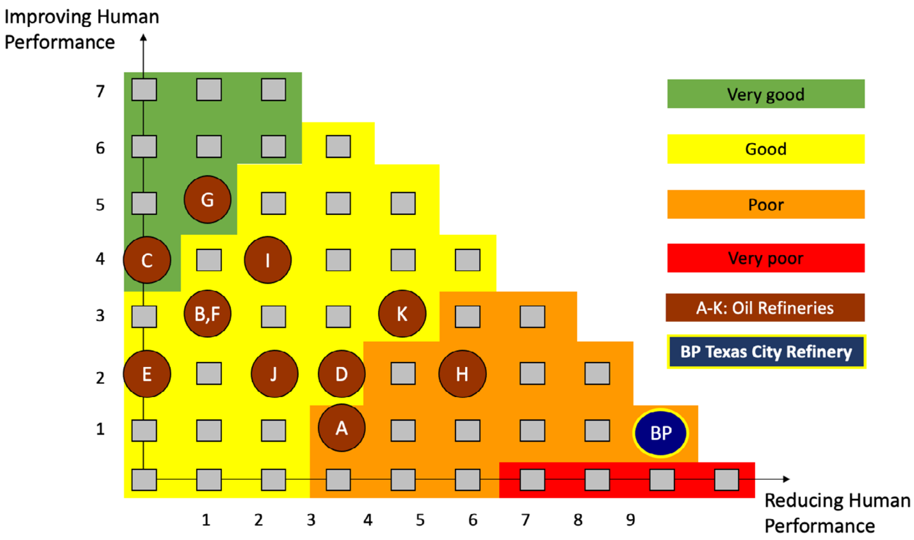



**FIGURE 3** The assessment of oil refineries using the HPI index [Color figure can be viewed at wileyonlinelibrary.com]

from the use of the questionnaire for the BP Texas city refinery (please see the supplementary material). To gain more confidence in the HPI index, the findings from the "surveyors" questionnaires were also compared with the overall assessment of the facilities, as obtained from the facilities audits. The same eight engineers conducted the audits and implemented the questionnaire. However, to ensure impartiality and avoid individual biases in the results, the surveyor(s) who graded the facilities with the HPI index were not the same with the auditor who produced the overall assessments for the same facility.

Figure 3 portrays the overall assessment of the refineries, while Table 5 presents the assessment of Common Performance Conditions (CPCs) for each facility. As it can be seen in Figure 3, the BP's Texas City plant was given a "poor" assessment. Results show that eight CPCs have a negative impact on human performance, while only the CPC "working conditions" was positively assessed. Considering the size of the BP Texas City accident it can be claimed that any refinery in this area of the chart represents facilities which demonstrate very poor human performance features and are susceptible to significant losses in case of accidents. Further, it can also be suggested that the identified boundaries and assumptions made for the development of the HPI index (dominant questions, weights, grades) reflect reality.

A few further observations can also be outlined. Plant H was "poorly" assessed from a human factors perspective with five CPCs to have a negative impact on its employees performance. It is regarded to represent a rather unsafe and prone to hazard facility. An accident in Plant H could result in significant losses. Similar to Plant H, Plants A, K, and D are all installations with more "negative" than "positive" CPCs. However, only one of the plants is located in the "poor" area of the chart. This observation may raise questions with respect to: (i) the accuracy of the assessment, especially in the areas of the chart adjacent to two control modes, and (ii) how the results may change if the "weighting" of the questions would be different. On the other hand, seven plants lie clearly within the "good" and "very good" performances, placing them on the positive side of the safety spectrum.

Several cultural traditions shall also be considered for the assessment, as suggested by more than one surveyor experts. For instance, more than 50 facilities worldwide are located in Muslim countries,[4] where during Ramadan the special conditions of daily fasting for approximately 30 consecutive days per year, may have an impact on the operators performance.[53] It is yet to define how to incorporate these conditions into the questionnaire and capture their potential impact on human performance. A suggestion is to produce more customized questionnaires including additional/different questions for some of the CPC categories, such as "Adequacy of Organisation", "Adequacy of Training and Experience" and "Fatigue".

The surveyors were also asked to provide feedback on the implementation of the questionnaire, its clarity and coherence, and indicate recommendations for its improvement. Their comments were:

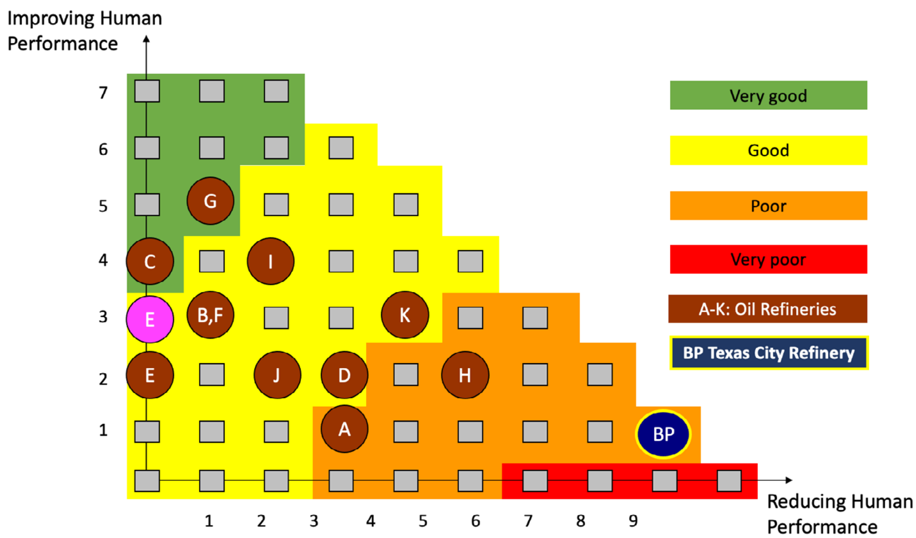
- The questionnaire is well structured and easy to apply
- The questionnaire did not demand a lot of effort for its completion; thus, it could be added to the standard auditing process without complications
- Although the questions are clear and well-defined, some are difficult to be observed and in turn answered, so they should probably be replaced or skipped. Examples of these questions include:
  - The supervisor acts calmly under pressure (crew collaboration)
  - The supervisor passes stress on employees (crew collaboration)
- A number of questions with low "weight" could also be replaced or skipped, for example
- Shift cycle (time of day–fatigue)
- Kind of transportation (time of day–fatigue)
- Dining room (working conditions)
- In the category "availability of procedure and plans" more specific questions on the availability and clarity of procedures, especially if they involve maintenance works, shall be added.

Based on the surveyors feedback the authors modified the questionnaire and re-assessed the facilities. First, the questions with the lowest weight on human performance were removed to confirm whether

**TABLE 5** The assessment of common performance conditions (CPCs) per facility using the HPI index

| | Adequacy of organization | Working conditions | Adequacy of MMI and operational support | Availability of procedures/ plans | Number of simultaneous goals | Time of day (Fatigue) | Available time | Crew Collaboration quality | Adequacy of training & experience |
|---|---|---|---|---|---|---|---|---|---|
| Plant A | Not significant | Reduced | Not significant | Reduced | Not significant | Not significant | Not significant | Improved | Reduced |
| Plant B | Improved | Not significant | Not significant | Improved | Not significant | Not significant | Improved | Not significant | Reduced |
| Plant C | Not significant | Not significant | Improved | Not significant | Improved | Not significant | Improved | Not significant | Improved |
| Plant D | Not significant | Reduced | Not significant | Improved | Not significant | Not significant | Reduced | Improved | Reduced |
| Plant E | Improved | Improved | Not significant | Not significant | Not significant | Not significant | Not significant | Not significant | Not significant |
| Plant F | Improved | Improved | Not significant | Reduced | Not significant | Not significant | Not significant | Improved | Not significant |
| Plant G | Improved | Improved | Improved | Improved | Not significant | Not significant | Not significant | Improved | Reduced |
| Plant H | Improved | Reduced | Reduced | Improved | Not significant | Reduced | Reduced | Reduced | Not significant |
| Plant I | Improved | Not significant | Improved | Improved | Not significant | Reduced | Improved | Not significant | Reduced |
| Plant J | Improved | Reduced | Not significant | Improved | Not significant | Reduced | Not significant | Not significant | Not significant |
| Plant K | Improved | Reduced | Reduced | Improved | Reduced | Not significant | Reduced | Improved | Not significant |

**FIGURE 4** The new assessment of oil refineries using the HPI index [Color figure can be viewed at wileyonlinelibrary.com]




their impact on HPI index was indeed insignificant. Then, a workshop was conducted with the surveyors to alter the weighting of the remaining questions. During the workshop it was also decided that the boundaries and grades of the CPCs should remain intact. The new assessment of the facilities, based on the modified questionnaire is shown in Figure 4. As it can be seen, the results are largely the same, with only Plant E to perform better and be placed in a better location. Subsequently, we argue that the changes in the questionnaire did not affect the results, while they also confirmed the initial findings.

Finally, the comparison of the HPI index findings against the overall assessment of the facilities showed that:

- Overall, the surveyors assessed Plants C and G very safe, and were unequivocally in favor of their insurance. The audit revealed that the employees working in plants C and G reside in modern compounds, and have a strong professional and personal relationship with each other. It was also found that the employees are overall satisfied with the management, they mainly focus on their duties, while any of their problems are sufficiently addressed by the company. The findings are in agreement with the rating of the facilities using the HPI index, as shown in Figure 3.
- Plants I, E, B and F received a positive evaluation. Nonetheless, some drawbacks were identified, which were consistent with the findings obtained from the implementation of the HPI index. To overcome the weaknesses and improve the facilities performance, the surveyors suggested specific recommendations to the management, i.e., strengthen training (Plants B and I), provide clearer and more straightforward safety procedures (Plant F).
- The surveyors handed over a positive, yet with restrictions, assessment for plants A, D and J. They did suggest the insurance of the facilities, but they did also request specific changes from the management beforehand. The changes involved the plants training

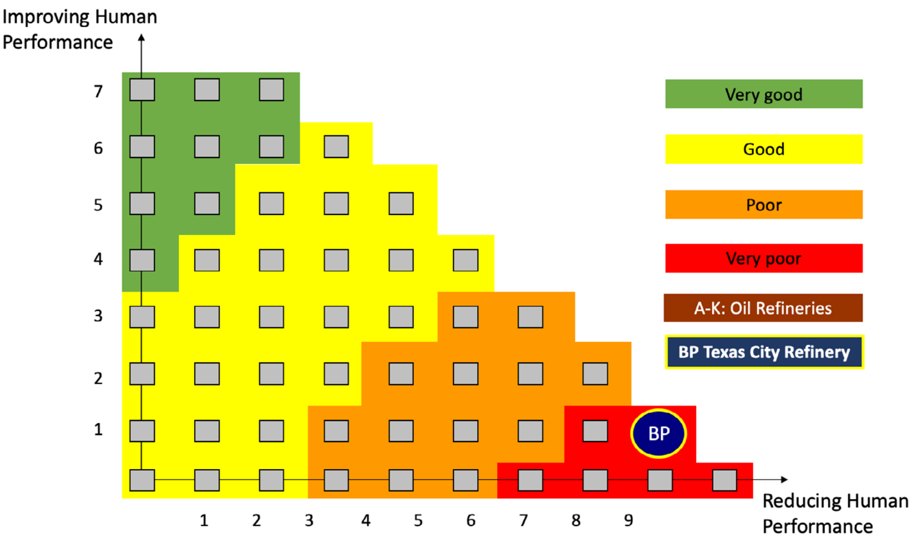



**FIGURE 5** The re-designed human performance chart [Color figure can be viewed at wileyonlinelibrary.com]

schedules (Plants A and D), working conditions (Plants A and J), and operators fatigue management (Plants D and J).

- Finally, Plant H was given a poor evaluation, despite the fact that is among the newest and more modern facilities. It is also noteworthy to mention that a few months prior to the audit an accident, which was attributed to organizational and human failures, occurred in the facility. Nonetheless, until the time of the audit the management did not implement any of the recommendations provided by the accident investigation committee. The surveyors proposed against the insurance of the installation, providing its poor working conditions, lack of procedures, troublesome collaboration between the employees, levels of fatigue and insufficient training. The surveyors assessment was also captured by the HPI questionnaire, as shown in Table 5.

## 4 | CONCLUSION

Despite the progress in the development of HRA techniques, several long-lasting limitations including the scarcity of data, and the limited capacity to capture the contribution of human and organizational factors in the dynamics of an accident are yet to be addressed.[44,54] To overcome current limitations, this study presented a novel approach, referred to as Human Performance Integrity (HPI) index, with a two-fold aim. First, to assess human performance, and in turn reliability, with respect to safety based on a set of factors that affect human performance. Second, to rate facilities in terms of their defenses against safety-relevant human failures, which can provide useful insights to risk management.

To defend this attempt and support the introduction of its new elements, the theoretical background and features of an acknowledged and well established HRA method were utilized. The HPI index is built upon the identification and assessment of a number of factors (PSFs) that affect the performance of operators in chemical installations, especially in oil refineries. The use of CREAM[45] was favored. The relevant PSFs were identified and associated to the CREAM's Common Performance Conditions. A questionnaire was conceived and implemented to collect data on the impact of PSFs on the performance of operators. The questionnaire was used to rate 11 facilities worldwide by eight surveyors during the inspection of the facilities for insurance purposes. The collected information provides useful insights on the facilities safety performance from a human factors perspective. Yet, certain limitations have to be addressed in future work.

First, the implementation of an additional questionnaire to capture the opinion of the facilities employees could bolster the HPI index findings. This questionnaire is currently under development and it is expected to be used in future audits. Its implementation, ensuring confidentiality, is expected to provide a more detailed assessment of the facilities and bridge any gap between the employees and management's viewpoint on the facilities safety and reliability from a human factors perspective. Second, the grading of the responses and weighting of the questions in the surveyors questionnaire have to be further verified. For this, additional surveys will be conducted to collect a larger and more representative pool of data, which in turn is anticipated to result in more reliable results. Third, similar to the traditional HRA techniques, the experts elicitation shall be additionally discussed. In this study, all surveyors were introduced and trained on how to use the questionnaire; thus, it can be claimed that possible individual biases have been avoided. Likewise, surveys shall be designed in such way to avoid biases stemming from different personal viewpoints and/or perceptions. Fourth, a more thorough analysis on the impact of PSFs on human performance could be carried out. This study assumed that all CPCs have the same influence on human performance. However, it should be considered whether some of the CPCs, under certain conditions, may have a more significant impact on human performance than others. Finally, the validation of the HPI index should be revisited. To date, results have been compared only against findings derived from a limited number of, publicly and non-publicly, accident investigation reports. The on-going use of the questionnaire, as part of the audit process of the facilities, will facilitate the validation of the findings using a more objective pool of data and overcoming possibly concerns of hindsight bias. Nonetheless, despite its current limitations, results support the use of the HPI index from novice and experienced scholars and/or practitioners as a quick and effortless, yet sound and efficient way to assess safety and reliability performance of oil refineries from a human factors perspective.

Based on the present findings, this paper also proposes a modification on the design of CREAM's performance chart for chemical plants. The graph in Figure 5 was conceived based on the BP' Texas City refinery assessment, and also compared against the results derived from the non-publicly investigation reports. We, therefore, suggest that the control mode "very poor" may be expanded and cover some of the area covered by the control mode "poor". The proposed modification will be further examined upon the completion of the additional surveys.

To conclude, the HPI index intends to serve as a complementary approach to assess safety of oil refineries. Its focus on human performance could be incorporated into the facilities safety assessment, which includes fire protection, process, and occupational safety. Although this study focused on oil refineries, we suggest that the HPI index could also be used for the safety assessment of other process industries, as well as sectors with certain modifications, e.g., the replacement of some PSFs. We expect that our results are relevant for all actors involved with the safety management of complex sociotechnical systems and critical infrastructure.

## ACKNOWLEDGMENTS

The authors would like to thank Prof. Wolfgang Kröger, and Messrs. Ernst Zirngast and Ulrich Straub for their constructive contribution to this work.

## AUTHOR CONTRIBUTIONS

**Miltos Kyriakidis:** Conceptualization; data curation; formal analysis; investigation; methodology; project administration; validation; visualization; writing-original draft; writing-review & editing. **Vinh Dang:** Formal analysis; methodology; supervision; writing-review & editing.

## ORCID

*Miltos Kyriakidis* https://orcid.org/0000-0002-0597-0634
*Vinh N. Dang* https://orcid.org/0000-0002-4921-2421

## REFERENCES

1. Vinnem JE, Bye R, Gran BA, et al. Risk modelling of maintenance work on major process equipment on offshore petroleum installations. *J Loss Prevention Process Indus*. 2012;25(2):274-292.
2. Bevilacqua M, Ciarapica FE. Human factor risk management in the process industry: a case study. *Reliability Eng Sys Safety*. 2018;169: 149-159.
3. Ramos M, Droguett E, Mosleh A, Moura M, Ramos Martins M. Revisiting past refinery accidents from a human reliability analysis perspective: the BP Texas City and the Chevron Richmond accidents. *Can J Chem Eng*. 2017;95:2293-2305.
4. Billege I. 700 refineries supply oil products to the world. *NAFTA*. 2009;60(7–8):401-403.
5. Wood MH, Fabbri L. Challenges and opportunities for assessing global progress in reducing chemical accident risks. *Progress Disaster Sci*. 2019;4:100044.
6. Bellamy LJ. The influence of human factors science on safety in the offshore industry. *J Loss Prevention Process Indus*. 1994;7(4):370-375.
7. Jahangiri M, Hoboubi N, Rostamabadi A, Keshavarzi S, Hosseini AA. Human error analysis in a permit to work system: a case study in a chemical plant. *Saf Health Work*. 2016;7(1):6-11.
8. Nivolianitou Z, Konstandinidou M, Christou M. Statistical analysis of major accidents in petrochemical industry notified to the major accident reporting system (MARS). *J Hazard Mater*. 2006;137:1-7.
9. Kirwan B. *A Guide to Practical Human Reliability Assessment*. London: Taylor & Francis; 1994.
10. Wreathall J, Roth E, Bley D, Multer J. *Human Reliability Analysis in Support of Risk Assessment for Positive Train Control*. Cambridge, MA, U.S.A: Federal Railroad Administration; 2003.
11. Abbassi R, Khan F, Garaniya V, Chai S, Chin C, Hossain KA. An integrated method for human error probability assessment during the maintenance of offshore facilities. *Process Safety Environ Protection*. 2015;94:172-179.
12. Gitahi Kariuki S, Löwe K. Increasing human reliability in the chemical process industry using human factors techniques. *Process Safety Environ Protect*. 2006;84(3):200-207.
13. Taylor C, Øie S, Gould K. Lessons learned from applying a new HRA method for the petroleum industry. *Reliability Eng Sys Safety*. 2020; 194:106276.
14. Bye, A., K. Laumann, C. Blackett, M. Rasmussen, S. Øie, K. van de Merwe, K. Øien, R. Boring, N. Paltrinieri, I. Wærø, S. Massaiu, and K. Gould. *The Petro-HRA Guideline*. Halden, Norway: IFE; 2017. https://www.researchgate.net/publication/326156394_The_Petro-HRA_Guideline.
15. Boring RL. In: Podofillini L, ed. *Adapting Human Reliability Analysis from nuclear power to oil and gas applications, in Safety and Reliability of Complex Engineered Systems*. London: CPC Press; 2015.
16. Boring RL. How many performance shaping factors are necessary for human reliability analysis. *10th Int Probabilistic Safety Assessment Management Conf*. 2010. https://www.osti.gov/servlets/purl/1010682.
17. Boring RL, Griffith CD, Joe JC. The measure of human error: direct and indirect performance shaping factors. *Joint 8th IEEE Conf Human Factors Power Plants / 13th Conf Human Perform, Root Cause Trending (IEEE HFPP & HPRCT)*. 2007;170-176.
18. Bye A, Lois E, Dang VN, et al. International HRA empirical study–phase 2 report results from comparing hra method predictions to simulator data from sgtr scenarios. *US Nuclear Regulatory Commission*. 2011;2:1-417.
19. De Ambroggi M, Trucco P. Modelling and assessment of dependent performance shaping factors through analytic network process. *Reliability Eng Sys Safety*. 2011;96(7):849-860.
20. Forester J, Kolaczkowski A, Cooper S, Bley D, Lois E. *ATHEANA user's Guide*. Washington, DC: United States Nuclear Regulatory Commission; 2007 https://www.nrc.gov/docs/ML0721/ML072130359.pdf.
21. Forester JA, Cooper SE, Kolaczkowski AM, Bley DC, Wreathall J, Lois E. *An Overview of the Evolution of Human Reliability Analysis in the Context of Probabilistic Risk Assessment*. Oak Ridge, TN: U.S. Department of Energy; 2009.
22. Groth KM. A data-informed model of performance shaping factors for use in human reliability analysis. *Proc 2009 Annual Conf European Soc Reliability*. 2009;231-238.
23. Hamilton IW, Clarke T. Driver performance modelling and its practical application to railway safety. *Appl Ergon*. 2005;36(2005):661-670.
24. Kim JW, Jung W. A taxonomy of performance influencing factors for human reliability analysis of emergency tasks. *J Loss Prevention Process Indus*. 2003;16:479-495.
25. Kyriakidis M, Kant V, Amir S, Dang VN. Understanding human performance in sociotechnical systems–steps towards a generic framework. *Safety Sci*. 2018;107:202-215.

26. Maag C, Schmitz M. Assessment of train driver's performance using a driving simulator. *3rd Int Conf Rail Human Factors*. 2009;1-9.
27. Mosleh A, Groth K. A performance shaping factors causal model for nuclear power plant human reliability analysis. 2010;2.
28. Priestley K, Lee G. Human factors in railway operations. *Int Conf Challenges Railway Transport Inform Age*. 2008;1-5.
29. Smith P, Kyriakidis M, Majumdar A, Ochieng WY. Impact of ERTMS on human performance in railway operations - European findings. *Transport Res Rec J Transport Res Board*. 2013;2374:83-92.
30. Vanderhaegen F. APRECIH: a human unreliability analysis method-application to railway system. *Control Eng Prac*. 1999;7:1395-1403.
31. Stanton N, Hedge A, Brookhuis K, Salas E, Hendrick H. *Handbook of Human Factors and Ergonomics Methods*. Boca Raton, Florida: CRC Press LLC; 2005.
32. Kyriakidis M, Majumdar A, Ochieng WY. The human performance railway operational index—a novel approach to assess human performance for railway operations. *Reliability Eng Syst Safety*. 2018;170:226-243.
33. RSSB. *Understanding Human Factors: A Guide for the Railway Industry*. London: Rail Safety and Standards Board; 2004.
34. Baker, A.J. *The Report of the BP U.S: Refineries Independent Safety Review Panel*. United States: BP; 2007. http://news.bbc.co.uk/2/shared/bsp/hi/pdfs/16_01_07_bp_baker_report.pdf
35. U.S. Chemical Safety and Hazard Investigation Board. *Investigation Report Tosco Avon Refinery*. Washington, DC: U.S. Chemical Safety and Hazard Investigation Board; 2001. https://www.csb.gov/assets/1/20/tosco_final_report.pdf?13752.
36. U.S. Chemical Safety and Hazard Investigation Board. *Investigation Report BP Texas City*. Washington, DC: U.S. Chemical Safety and Hazard Investigation Board; 2007. https://www.csb.gov/bp-america-refinery-explosion/.
37. Hsu SH, Lee C-C, Wu M-C, Takano K. A cross-cultural study of organizational factors on safety: Japanese vs. Taiwanese oil refinery plants. *Accident Analysis Prevention*. 2008;40(1):24-34.
38. Luquetti dos Santos IJA, França JEM, Santos LFM, Haddad AN. Allocation of performance shaping factors in the risk assessment of an offshore installation. *J Loss Prevention Process Indus*. 2020;64:104085.
39. Strand G-O, Lundteigen MA. Human factors modelling in offshore drilling operations. *J Loss Prevention Process Indus*. 2016;43:654-667.
40. Zarei E, Yazdi M, Abbassi R, Khan F. A hybrid model for human factor analysis in process accidents: FBN-HFACS. *J Loss Prevention Process Indus*. 2019;57:142-155.
41. Rostamabadi A, Jahangiri M, Zarei E, Kamalinia M, Banaee S, Samaei MR. A novel fuzzy Bayesian network-HFACS (FBN-HFACS) model for analyzing human and organization factors (HOFs) in process accidents. *Process Safety Environ Protection*. 2019;132:59-72.
42. Xie X, Guo D. Human factors risk assessment and management: process safety in engineering. *Process Safety Environmen Protection*. 2018;113:467-482.
43. Kyriakidis M. *Developing a human performance railway operational index to enhance safety of railway operations, in Civil and Environmental Engineering*. London, UK: Imperial College London; 2013.
44. Di Pasquale V, Iannone R, Miranda S, Riemma S. In: Schiraldi M, ed. *An Overview of Human Reliability Analysis Techniques in Manufacturing Operations, in Operations Management*. London: InTech; 2013:221-240.
45. Hollnagel E. *Cognitive Reliability and Error Analysis Method*. Amsterdam, The Netherlands: Elsevier; 1998.
46. Konstandinidou M, Nivolianitou Z, Kiranoudis C, Markatos N. A fuzzy modeling application of CREAM methodology for human reliability analysis. *Reliability Eng Sys Safety*. 2006;91(6):706-716.
47. Akyuz E, Celik M. Application of CREAM human reliability model to cargo loading process of LPG tankers. *J Loss Prevent Process Indus*. 2015;34:39-48.
48. Sun Z, Li Z, Gong E, Xie H. Estimating human error probability using a modified CREAM. *Reliability Eng Sys Safety*. 2012;100:28-32.
49. Phillips RO, Sagberg F. What did you expect? CREAM analysis of hazardous incidents occurring on approach to rail signals. *Safety Sci*. 2014;66:92-100.
50. Ung S-T. A weighted CREAM model for maritime human reliability analysis. *Safety Sci*. 2015;72:144-152.
51. Zhou Q, Wong YD, Loh HS, Yuen KF. A fuzzy and Bayesian network CREAM model for human reliability analysis – the case of tanker shipping. *Safety Sci*. 2018;105:149-157.
52. Embrey D, Humphreys P, Rosa EA, Kirwan B, Rea K. *SLIM-MAUD: an Approach to Assessing Human Error Probabilities Using Structured Expert Judgment*. Vol 1. Washington, DC: Overview of SLIM-MAUD; 1984 https://www.researchgate.net/publication/236536121_SLIM-MAUD_an_approach_to_assessing_human_error_probabilities_using_structured_expert_judgment_Volume_I_Overview_of_SLIM-MAUD.
53. IPIECA. *Managing Fatigue in the Workplace*. London: International Association of Oil & Gas Producers; 2019. https://www.ipieca.org/media/4738/manging_fatigue_sheets_2019.pdf.
54. Swain AD. Human reliability analysis: need, status, trends and limitations. *Reliability Eng Sys Safety*. 1990;29:301-313.

## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Kyriakidis M, Dang VN. A scoping method for human performance integrity and reliability assessment in process industries. *Proc Safety Prog*. 2021; e12260. https://doi.org/10.1002/prs.12260