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A Knowledge-Based Recommender System for Personalized Fatigue Mitigation Strategies in Offshore Workers

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Abstract

Fatigue is a major safety concern in high-risk industries and can result from insufficient sleep, prolonged mental workload, and sustained physical exertion. While existing fatigue management approaches often focus on scheduling or generic interventions, they rarely provide personalized recommendations tailored to a worker's current fatigue condition. To address this gap, a personalized fatigue mitigation recommendation system was designed to support fatigue risk management in offshore oil and gas extraction (OGE) operations. The system integrates research evidence and offshore expert consensus within a multi-criteria decision-making framework to generate individualized fatigue mitigation strategies based on workers' fatigue profiles. The system considers four fatigue-related indicators: mental exhaustion, physical exertion, perceived sleepiness, and sleep loss. The recommendation system was applied to a real-world offshore fatigue dataset containing over 1,800 fatigue records collected from workers. Results demonstrated the feasibility of generating context-aware and personalized recommendations across a wide range of fatigue states.

Keywords

Worker fatigue, oil and gas industry, decision support system, knowledge-based recommender system, multi-criteria decision-making, safety management systems (SMS), fatigue risk management systems (FRMS), personalized recommendation, fatigue mitigation, occupational safety

Introduction

Fatigue is described as a state of feeling very tired, weary, or sleepy resulting from insufficient sleep, prolonged mental or physical work, or extended periods of stress or anxiety (Canadian Centre for Occupational Health and Safety, 2017). In high-risk industries such as oil and gas extraction (OGE), fatigue has been identified as a key causal factor in human-error-associated industrial incidents (Theophilus et al., 2017). As a result, evidence-based fatigue risk management has become an important component of maintaining operational performance, worker health, and workplace safety across safety-critical domains (Caldwell et al., 2019). Industry guidelines in the OGE sector have outlined core components of fatigue risk management systems (FRMS), including fatigue monitoring, mitigation strategies, and organizational support mechanisms (API, 2019; COS, 2024).

Operational fatigue management programs have been implemented across multiple safety-critical domains, including military operations (Shattuck & Matsangas, 2022), emergency response (Barger et al., 2017), transportation (Smiley et al., 2009), and healthcare (Dara, 2019). These programs have emphasized practical fatigue mitigation approaches such as strategic scheduling, sleep optimization, circadian management, and supervisory support. These existing fatigue risk management systems have demonstrated the importance of integrating fatigue mitigation into operational decision-making processes in safety-critical environments. However, these approaches primarily focus on organization-level fatigue management and generalized mitigation guidance rather than individualized recommendations tailored to a worker's current fatigue profile.

Recent advances in fatigue monitoring research have demonstrated the feasibility of collecting individual fatigue-related data in operational environments using subjective reports, behavioral measures, and physiological sensing technologies (Kang et al., 2025). Previous research has also proposed individualized fatigue intervention protocols integrating fatigue assessment with intervention delivery. For example, Patterson et al. (2017) developed a fatigue mitigation protocol in which fatigue levels assessed via self-reports triggered intervention messages when high fatigue was detected. This approach demonstrated positive short-term

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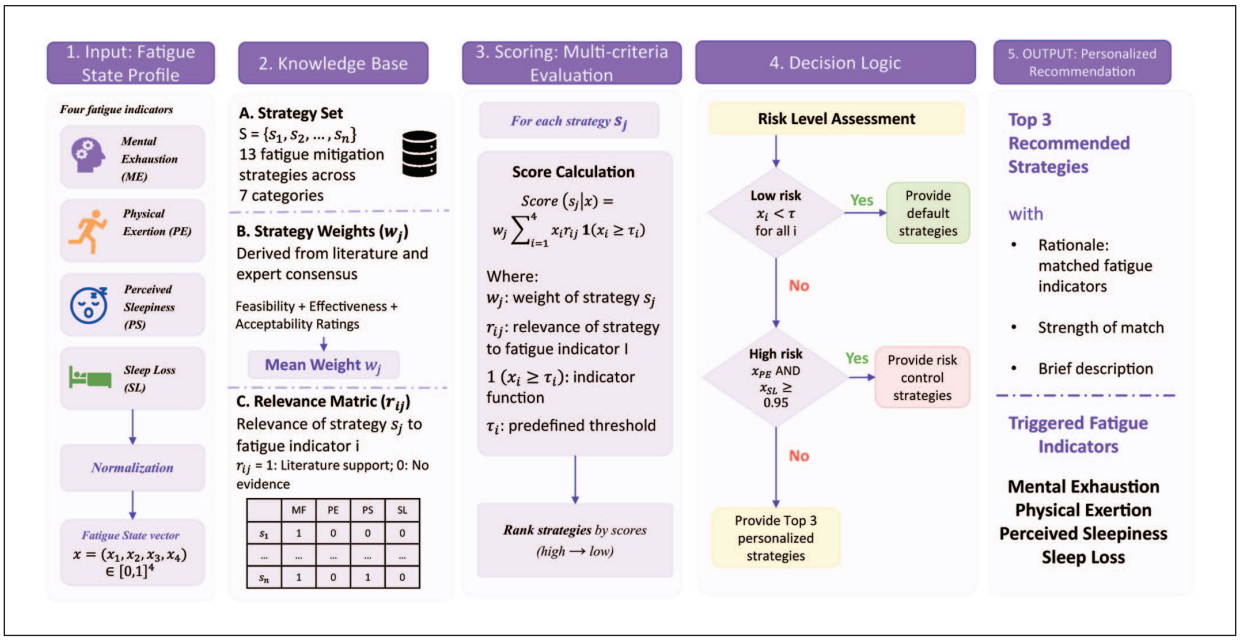


Figure 1. Architecture of the fatigue mitigation strategy recommendation system

effects in reducing fatigue among emergency medical personnel (Patterson et al., 2019). However, the intervention messages were randomly selected from a predefined set of strategies and were not tailored to the individual's specific fatigue state, limiting the ability to provide condition-specific and personalized fatigue mitigation.

In operational contexts, fatigue can arise from multiple interacting contributors, including insufficient sleep, prolonged mental workload, and sustained physical exertion, each of which affects performance and recovery through distinct physiological and cognitive mechanisms (Dawson et al., 2011). Therefore, it is important to conceptualize fatigue as a multidimensional construct and provide effective mitigation strategies aligned with the specific fatigue dimensions being experienced. Accordingly, there remains a lack of frameworks capable of translating multidimensional fatigue state information into actionable and personalized fatigue mitigation recommendations. This remains an important gap, particularly given the substantial inter-individual variability in fatigue experiences, contributing factors, and recovery needs (Caldwell et al., 2019).

To address this gap, we developed a knowledge-based fatigue mitigation recommendation system that generates personalized mitigation strategies based on individual fatigue state profiles using a multi-criteria decision-making framework. In the present study, the system was operationalized using fatigue measures collected within an existing offshore dataset. Meanwhile, the proposed recommendation system serves as a decision-support component within a broader digital fatigue risk management system intended to support both workers and supervisors in operational environments. The digital FRMS includes data-collection components, evidence-informed backend recommendation models, and frontend dashboard interfaces designed to support fatigue-management decision-making for workers and supervisors.

This study aims to: (1) develop a personalized fatigue mitigation recommendation system based on empirical evidence and expert consensus; and (2) apply and demonstrate the system using data collected from offshore OGE workers.

Approach

A recommendation system was developed based on empirical evidence and offshore FRMS expert consensus (Cai et al., 2026). As shown in Figure 1, the recommendation system integrates a knowledge base containing fatigue. indicators, mitigation strategies, expert-derived strategy weights, and evidence-based relevance relationships, together with a recommendation engine to generate personalized fatigue mitigation strategies based on individual fatigue-state profiles.

Knowledge Base of the System

Fatigue Indicators. Fatigue state was conceptualized as a multidimensional construct characterized by four indicators that capture both fatigue manifestations and contributing factors: mental exhaustion, physical exertion, perceived sleepiness, and sleep loss. These four dimensions were selected to capture complementary aspects of fatigue that are commonly identified in fatigue risk management systems and prior literature (Caldwell et al., 2019; Sinagabariang & Kurniawidjaja, 2024).

Importantly, the proposed system is measurement-agnostic. Each fatigue indicator is defined at the conceptual level and can be operationalized using different data sources (e.g., subjective reports, behavioral measures, or physiological

Table 1. Fatigue Mitigation Strategies, Weights, and Relevance Matrix.

Strategy	ME	PE	SL	PS	Default	Risk control	F	E	A	Mean
Reschedule safety critical tasks		1				Yes	4.25	4.25	4.25	4.25
Encourage worker to take breaks	1	1		1		Yes	4.25	4.25	4.25	4.25
Temporary reassignment or additional staffing	1	1				Yes	2.5	3.19	3.13	2.94
Minimize overtime hours		1	1		Yes		2.81	3.56	3.25	3.21
Offer melatonin with proper instruction			1	1			4.5	4.25	4.25	4.33
Remind worker to ensure sufficient sleep duration and get adequate rest			1	1	Yes		4.75	4	3.5	4.08
Improve supervisor monitoring and support	1	1	1		Yes		4.75	4.5	4.75	4.67
Facilitate leisure activities during non-work hours	1		1				3	4.25	4.25	3.83
Encourage working in pairs		1					3.75	5	4.5	4.42
Promote social interactions and peer support	1						4.25	4.75	5	4.67
Promote exercises/physical activities	1	1	1				3.75	4.5	4.5	4.25
Encourage maintaining a healthy diet	1		1	1			3.92	3.92	3.58	3.81
Improve sleep environment			1	1			4.25	5	5	4.75

ME: Mental Exhaustion, PE: Physical Exertion, SL: Sleep loss, PS: Perceived Sleepiness, F: Feasibility, E: Effectiveness, A: Acceptability.

signals). In the present study, fatigue indicators were operationalized based on an existing offshore dataset (Kang et al., 2025). Specifically:

- Mental exhaustion (ME) was assessed using a 5-point Likert scale ranging from low to high perceived mental fatigue.
- Physical exertion was measured using Borg's Rating of Perceived Exertion (RPE) scale, which is widely used to quantify perceived physical fatigue (Borg, 1998).
- Perceived Sleepiness (PS) was assessed using the Karolinska Sleepiness Scale, a validated 9-point scale commonly used in fatigue and sleep research in the OGE industry (Shahid et al., 2011).
- Sleep loss (SL) was computed as the difference between the recommended guideline of at least 7 hours of sleep per night (Ford et al., 2015) and the actual sleep duration reported for the previous night. Sleep duration was objectively measured using wrist-worn actigraphy devices,

The combination of subjective and objective measures reflects the practical constraints of offshore environments while ensuring adequate coverage of key fatigue dimensions. This data collection protocol has been previously applied in offshore fatigue studies, demonstrating feasibility in operational environments (Kang et al., 2025). Prior to input into the recommendation engine, all fatigue indicators were normalized to the [0,1] scale to ensure comparability across dimensions.

Fatigue Mitigation Strategies. A set of candidate fatigue-mitigation strategies was compiled from a previous study (Cai et al., 2026). Through a systematic review and a two-round Delphi consensus study involving 14 offshore FRMS experts, a total of 28 fatigue risk management strategies were identified across seven categories, including work scheduling, light treatment, melatonin, education and training, supervisor/peer/organizational support, lifestyle and personal habits, and work and sleep environments.

To provide personalized, daily intervention recommendations at the individual level, the present study included a subset of 13 strategies that can be implemented by workers and/or their direct supervisors. Organizational-level strategies were excluded, as they are less actionable in real-time or short-term decision-making contexts. Based on expert ratings of feasibility, effectiveness, and acceptability, each strategy was assigned a weight calculated as the average of these three criteria.

To establish evidence-based associations between fatigue indicators and mitigation strategies, a *relevance matrix* (r_{ij}) was constructed based on the literature findings. For each indicator i and strategy j, r_{ij} was assigned a value of 1 was assigned if empirical evidence demonstrated that the strategy mitigates that indicator and 0 if it does not. Evidence supporting these associations was synthesized from prior fatigue and sleep research across operational domains with a primary focus on the offshore OGE industry. (e.g., Alroomi & Mohamed, 2022; McNamara & Robbins, 2023; Parkes, 2017). The list of strategies, along with their corresponding weights and relevance matrix, is summarized in Table 1.

Recommendation Engine

Inputs and Normalization. For each worker and time point, x_i represents the normalized fatigue indicator level. For each worker at a given time point, the fatigue state was represented as a vector

$$x = (x_1, x_2, x_3, x_4) \quad (1)$$

where each $x_i \in [0,1]$ corresponds to a normalized fatigue indicator. Normalization was performed to align different measurement scales into a unified range. For subjective scales (e.g., Likert, RPE, KSS), values were linearly rescaled to the [0,1] range using their respective minimum and maximum values. Sleep loss was transformed to a [0,1] range, where sleep deficits between 0 and 2 hours were linearly scaled, and values greater than or equal to 2 hours were capped at 1.

Scoring Layer. For each strategy, a score is computed as:

$$Score\left(s_j|x\right) = w_j \sum_i^4 x_i r_{ij} \mathbf{1}\left(x_i \geq \tau\right) \quad (2)$$

where r_{ij} represents the relevance between fatigue factor i and strategy j, and w_j represents the Delphi-derived strategy weight, reflecting its feasibility, effectiveness, and acceptability in the offshore OGE setting. The function $\mathbf{1}(x_i \geq \tau)$ serves as an indicator function that activates the indicator i only when its value exceeds the predefined threshold τ.

The threshold τ was set to 0.6 to focus the recommendation process on salient fatigue indicators, thereby reducing noise from low-level fatigue signals. This threshold was determined based on preliminary sensitivity testing to balance responsiveness and specificity. Strategies were ranked in descending order based on their computed scores.

Decision Layer. To ensure robustness under different fatigue conditions, additional rule-based decision logic was incorporated. These rules were designed to reflect operational priorities and safety considerations in offshore environments:

- Low-fatigue condition: Default strategies were selected when all fatigue indicators were below predefined thresholds (IF $\forall i, x_i < \tau$, THEN select default fatigue mitigation strategies).
- High-risk condition: Risk-control strategies were triggered when both physical exertion and sleep loss exceeded critical thresholds (IF $x_{PE} \geq 0.95$ AND $x_{SL} \geq 0.95$, THEN select risk control strategies).
- General condition: In all other cases, the top three strategies based on the scoring model are selected.

Outputs. The system output included the top 3 recommended fatigue mitigation strategies and the primary fatigue indicators driving each recommendation. This output structure is intended to support both decision-making and interpretability, allowing users to understand the rationale behind each recommendation.

Simulation Study

The recommendation system was evaluated using a fatigue dataset collected as part of a prior longitudinal offshore study (Kang et al., 2024). The dataset included 70 workers from two offshore drillships in the Gulf of Mexico over a 28-day hitch.

A total of $N = 1{,}816$ valid fatigue records were obtained, each containing complete data on mental exhaustion, physical exertion (RPE), sleepiness (KSS), and sleep duration. Sleep loss was computed as the difference between recommended and observed sleep duration, measured with wrist-worn actigraphy.

Each record was treated as an independent fatigue state input to the recommendation engine. The simulation aimed to evaluate the system's behavior across a wide range of fatigue states observed in real-world offshore operations.

Outcomes

Application of the recommendation system to the offshore fatigue dataset demonstrated the feasibility of generating personalized fatigue mitigation recommendations across heterogeneous fatigue-state profiles. Table 2 summarizes representative fatigue-state combinations, corresponding decision conditions, triggered fatigue indicators, and the top recommended mitigation strategies generated by the system. The cases presented are intended to illustrate representative recommendation patterns generated by the system rather than provide an exhaustive list of all possible outputs. Importantly, recommendation outputs may vary even within the same triggered fatigue-indicator combination, as the final strategy ranking is influenced by the relative severity and magnitude of the underlying fatigue indicators. The recommendation patterns varied according to the dominant contributors to fatigue.

Among the 1,816 valid fatigue records, low-fatigue conditions represented the largest proportion of cases ($k = 614$), in which all fatigue indicators remained below predefined thresholds. Under these conditions, the system generated default preventive strategies focused on maintaining general recovery and fatigue management behaviors, including supervisor monitoring, adequate rest, and minimizing overtime exposure.

The majority of remaining records were categorized under the general recommendation condition, in which one or more fatigue indicators exceeded the activation threshold. The recommendation patterns varied substantially depending on the combination of triggered fatigue contributors. For example, cases characterized primarily by elevated mental exhaustion (ME) frequently resulted in recommendations emphasizing social support, supervisory monitoring, and recovery-related activities. In contrast, records dominated by elevated physical exertion (PE) generated recommendations focused on workload management, operational support, and regular exercise, including working in pairs, encouraging breaks, and supervisor support. Sleep-related fatigue profiles characterized by elevated perceived sleepiness (PS) and/or sleep loss (SL) were more likely to trigger recommendations for sleep recovery, including improving the sleep environment, encouraging adequate sleep duration, and melatonin-related

Table 2. Example Recommendation Outputs Under Different Fatigue States.

No.	ME (1–5)	RPE (6-20)	KSS (1–9)	SL (hrs)	Decision condition	Triggered factors	Factors combination proportion (k/1816)	Best three strategies recommended
1	2	12	3	0.45	Low -fatigue	–	614	Improve supervisor monitoring and support; Remind the worker to ensure sufficient sleep and get adequate rest; Minimize overtime hours
2	2	20	2	3.3	High –risk	–	2	Reschedule safety-critical tasks; Encourage the worker to take breaks; Temporary reassignment
3	4	13	5	0.05	General	ME	411	Promote social interactions and peer support; Improve supervisor monitoring and support; Promote exercises/physical activities
4	2	19	4	0	General	PE	105	Improve supervisor monitoring and support; Encourage working in pairs; Promote exercises/physical activities
5	1	14	2	4.7	General	SL	261	Improve sleep environment; Improve supervisor monitoring and support; Offer melatonin with proper instruction
6	4	16	1	0.47	General	ME, PE	101	Improve supervisor monitoring and support; Promote exercises/physical activities; Encourage the worker to take breaks
7	4	14	8	1.23	General	ME, PS	89	Encourage the worker to take breaks; Encourage maintaining a healthy diet; Improve sleep environment
8	3	16	1	3.35	General	ME, PE, SL	20	Improve supervisor monitoring and support; Promote exercises/physical activities; Facilitate leisure activities during non-work hours
9	2	14	6	0.77	General	PS	27	Improve sleep environment; Offer melatonin with proper instruction; Encourage worker to take breaks
10	4	13	1	1.66	General	ME, SL	87	Improve supervisor monitoring and support; Promote exercises/physical activities; Facilitate leisure activities during non-work hours
11	2	17	6	0	General	PE, PS	1	Encourage worker to take breaks; Improve supervisor monitoring and support; Encourage working in pairs
12	2	19	3	1.35	General	PE, SL	30	Improve supervisor monitoring and support; Promote exercises/physical activities; Minimize overtime hours
13	5	20	1	1.6	General	ME, PE, SL	20	Improve supervisor monitoring and support; Promote exercises/physical activities; Encourage worker to take breaks
14	2	13	6	1.5	General	PS, SL	8	Improve sleep environment; Offer melatonin with proper instruction; Remind worker to ensure sufficient sleep duration and get adequate rest
15	4	14	8	1.2	General	ME, PS, SL	36	Encourage maintaining a healthy diet; Encourage worker to take breaks; Improve sleep environment
16	1	16	7	2.6	General	PE, PS, SL	3	Improve sleep environment; Improve supervisor monitoring and support; Offer melatonin with proper instruction
17	4	16	7	0	General	ME, PE, PS	19	Encourage worker to take breaks; Improve supervisor monitoring and support; Promote exercises/physical activities
18	4	17	8	2.5	General	ME, PE, PS, SL	2	Improve supervisor monitoring and support; Promote exercises/physical activities; Encourage worker to take breaks

ME: Mental Exhaustion, PE: Perceived Exertion, measured with Borg's Rating of Perceived Exertion (RPE), PS: Perceived Sleepiness, measured with Karolinska Sleepiness Scale (KSS), SL: Sleep Loss.

interventions. Multi-factor fatigue conditions generally led to more comprehensive mitigation recommendations that integrated workload management, adequate rest, and supervisory support strategies.

Discussion

By integrating empirical evidence, expert consensus, and rule-based decision logic within a multi-criteria decision-making framework, the proposed system extends previous fatigue management approaches beyond generalized fatigue guidance to deliver individualized, interpretable fatigue mitigation recommendations. The recommendation logic was informed by weighted-sum approaches commonly used in multi-criteria decision-making, where multiple weighted criteria are aggregated to evaluate and rank candidate alternatives (Kumar & Parimala, 2020).

In offshore operational contexts, fatigue can arise from multiple interacting contributors, including insufficient sleep, prolonged mental workload, and sustained physical exertion (Sinagabariang & Kurniawidjaja, 2024). Therefore, it is important to conceptualize fatigue as a multidimensional construct rather than a single generalized state. The present study addressed this need by developing a knowledge-based recommendation system that maps different combinations and severities of fatigue contributors to tailored mitigation strategies. The process used to identify fatigue mitigation strategies in the present study is conceptually aligned with previous efforts in other domains. For example, Patterson et al. (2018) developed evidence-based FRMS guidelines for emergency medical services providers through a literature review and expert evaluation. Similarly, the fatigue mitigation strategies used in the present framework were derived from a previous multi-phase process that integrated peer-reviewed literature, industry FRMS guidelines, and operational FRMS documents from offshore companies. Furthermore, strategies reached consensus among offshore FRMS experts on their feasibility, effectiveness, and acceptance were retained (Cai et al., 2026). By incorporating scientific evidence and practical operational perspectives, the strategy inventory was intended to balance intervention effectiveness with operational feasibility and real-world applicability.

Compared with previous fatigue intervention systems that primarily deliver generic or randomly selected fatigue messages (Patterson et al., 2019; Sprajcer et al., 2022), the present system incorporates individualized recommendation logic based on the relative severity and combination of fatigue contributors. In addition, the system provides interpretable outputs by explicitly identifying the fatigue indicators contributing to each. This transparency may support worker understanding, supervisor decision-making, and trust calibration in the recommendation system, facilitating future integration into operational settings (Zerilli et al., 2022).

Several limitations should also be acknowledged. First, the present study primarily demonstrated the system's recommendation logic and feasibility, rather than evaluating the effectiveness of the recommended interventions in operational settings. Second, the recommendation weights and relevance matrix were constructed based on existing literature and expert consensus, which may evolve as additional evidence becomes available. Although the present implementation primarily utilized subjective fatigue indicators due to operational feasibility and dataset availability, the proposed framework is measurement-agnostic and may incorporate subjective, behavioral, physiological, or multimodal fatigue measures in future implementations, depending on data availability.

Future work will involve deploying and evaluating the recommendation system in operational offshore environments by integrating it with fatigue management dashboards and field data collection systems. Such deployment studies will evaluate worker compliance, acceptance of recommendations, operational usability, and the longitudinal effectiveness of personalized fatigue mitigation strategies. In addition, future versions of the system may incorporate adaptive learning that iteratively refines recommendation logic based on user feedback, intervention outcomes, and continuously collected operational data.

Conclusion

This study developed a knowledge-based fatigue mitigation recommendation system that generates personalized strategies based on individual fatigue-state profiles using a multi-criteria decision-making framework. By integrating research-based evidence and expert ratings of mitigation strategies, the system provides tailored and context-aware fatigue mitigation recommendations. Application of the system to an offshore fatigue dataset demonstrated the feasibility of generating differentiated mitigation strategies across heterogeneous fatigue conditions. The present study provides a practical framework for translating fatigue-state information into personalized, actionable mitigation recommendations. This approach represents a practical decision-support tool to enhance fatigue risk management and support worker safety in high-risk operational environments.

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