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A Safety Risk Management Approach Using Human Factor Analysis and Classification System (HFACS) Based Investigation for Urban Railway Maintenance Accidents

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Abstract

Despite the growth and modernization of the Malaysian railway industry, human factors remain a primary cause of workplace accidents. This research explores the human factors contributing to workplace accidents among maintenance workers in Malaysia's urban railway sector using the Human Factors Analysis and Classification System (HFACS). The research employs qualitative methods, including interviews with five maintenance workers who have experienced workplace incidents, along with a comprehensive review of 14 accident reports from 2017 to 2021. Findings reveal that unsafe acts are significant contributors to accidents, accounting for 28.6% of reported cases. These errors are often caused by distractions due to internal factors, such as excessive work pressure, or external factors, such as environmental disturbances. Preconditions for unsafe acts, including hazardous physical environments, emerged as the most frequent cause, representing 50% of cases. Other contributing factors include improper tool use (7.1%) and deficiencies in communication, coordination, and planning during routine maintenance tasks (14.3%). The findings from the interview session indicate that most workplace accidents were linked to unsafe acts, with 80% of respondents highlighting these as major causes. Respondents also identified preconditions such as physical environment, mental and physical states, and sensory misperception, in which 20% cited poor lighting, confined spaces, fatigue, and misreading instruments as key factors. Though supervisory issues were rarely mentioned, 20% of respondents blamed organisational shortcomings, such as lack of essential tools and poor resource management, for contributing to unsafe conditions. Preventive measures, such as wearing personal protective equipment (PPE) and fostering team-based monitoring in high-risk environments, were emphasised by respondents. This research accentuates the importance of applying the HFACS framework as a diagnostic tool, human-related contributing factors to railway maintenance accidents can be systematically identified, enabling the development of targeted interventions to enhance safety and reduce workplace incidents in railway maintenance operations.

1. Introduction

The railway industry, particularly in industrial rail transportation, faces significant challenges in terms of safety and occupational hazards. Accidents can have detrimental effects on both jobs and the environment, underscoring the importance of rigorous maintenance and inspection protocols. Daily inspections are crucial to ensure the safe operation of tracks and to mitigate potential incidents, thereby providing users with comfort and safety.

Accidents in the railway industry can be attributed to a variety of factors, including human error, workplace conditions, and environmental factors. Investigations into these incidents often reveal that human mistakes play a significant role. Moreover, employment as a railway technician exposes individuals to numerous occupational hazards, such as ergonomic challenges, chemical exposure, and noise pollution. Regular maintenance tasks, including fueling and mechanical inspections, cleaning the exteriors of locomotives and the interiors of rail tank trucks [1], are critical but also pose risks to workers due to the use of heavy machinery and exposure to harmful substances.

Research has highlighted the prevalence of biomechanical risk factors among railway workers, including repetitive lifting and inadequate health and safety priorities [2]. Additionally, the frequent use of heavy machinery and exposure to vibrations and noise emissions are significant sources of discomfort for workers. Injuries in the railway industry can range from minor to life-threatening and include conditions such as lung cancer, mesothelioma, and hearing loss [3].

Human factors are a primary cause of industrial accidents, emphasising the need for strategies to reduce human error and enhance workplace safety [4]. Preventing human factors-related accidents should focus on reducing human error and providing safe working conditions to mitigate associated risks, such as decreased productivity, asset destruction, pollution, and fatalities [5]. While it is impossible to predict or plan for all workplace accidents, raising employee awareness of risks can reduce unnecessary risk-taking and mitigate the severity of accidents.

The railway industry's safety challenges necessitate a comprehensive approach that addresses both human factors and environmental conditions. By understanding the causes of accidents and prioritising employee health and safety, it is possible to mitigate risks and improve overall safety in the industry. This involves not only implementing rigorous maintenance protocols but also adopting frameworks like the Human Factors Analysis and Classification System (HFACS) to evaluate and address human factors contributing to accidents [6].

By utilising the HFACS approach, the human factors that contribute to accidents and incidents among maintenance workers will be identified and analysed systematically. The approach provides a structured framework for classifying errors at multiple levels, whether it is unsafe acts, preconditions for unsafe acts, supervisory factors, or organisational influences. Having this element identified could mirror best practices in safety risk management. Thus, this research employs the HFACS model to identify and assess factors contributing to occupational accidents within the scope of human factors targeted among railway maintenance workers.

2. Literature Review

2.1 Human Factors

As our local rail services have grown over the last 10 years, the introduction of new technology and modernisation has made the transportation services more competitive and vibrant. However, increased automation may not necessarily result in improved safety. Heavy reliance on automated processes may also result in complicity in human behaviour [7], which indicates human factors in a wider context, and particularly, human error. Human factors have been recognised as contributors to the majority of accidents in complex systems, including the railway system [8-13]. Failure to capture latent causes, especially from a human factors perspective, will result in the recurrence of incidents, causing large and small losses, injuries, and fatalities that impact on-time and cost-effective operations. Thus, accidents are to be further reduced by emphasising human factors as they relate to accident causation [14]. Common perspectives on human factors include individual, behavioural, cognitive, psychosocial, ergonomic and organisational [15].

Identification of human error has been vigorously pursued in international studies using a variety of approaches available. Types of human factors or errors involved in railway accidents include communication errors [16-17]. There has also been a large amount of research unfolding and identifying common railway accidents and incidents, such as Signals Passed at Danger (SPAD)-related errors from the perspective of

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behavioural [18] and information processing or cognitive tasks [19]. Other human factors/errors which have been reviewed and identified, such as the train drivers' tasks and roles [20-21], maintenance personnel [22-23], signalers [24] and latent failures (specifically managerial deficiencies) in the scope of staff attitude, operating equipment and maintenance [25]. In another study conducted in the Australian railway by [26], it revealed that 'skill-based errors' were the main driver of errors leading to Australian railway accidents and incidents. The causes of the errors were identified as the result of slips in attention, which apparently resulted from the 'preconditions' of decreased alertness and fatigue. In addition, the findings also indicated that the formation of incorrect expectations and assumptions was a common precondition for driver errors [29]. On top of that, it was discovered that the skill-based error was due to equipment failure, which was the result of inadequate maintenance or monitoring programs. For example, inspection of equipment was not performed, and in the cases where it had been conducted, inspections failed to detect long-standing equipment defects. Inadequate inspections allow misaligned or unstable tracks to go unnoticed, resulting in derailment [28].

2.2 Human Factors Analysis and Classification Systems (HFACS)

The Human Factors Analysis and Classification System (HFACS) is a classification framework developed by Wiegmann and Shappell [4, 14-15]. Rooted in Reason's Swiss Cheese theory (Reason, 1990, cited in [28]), HFACS describes human error and system failures within 4 levels of error causation [29,30]. The four distinct layers are organisational influences (Level 4), supervisory factors (Level 3), preconditions for unsafe acts (Level 2), and unsafe acts (Level 1).

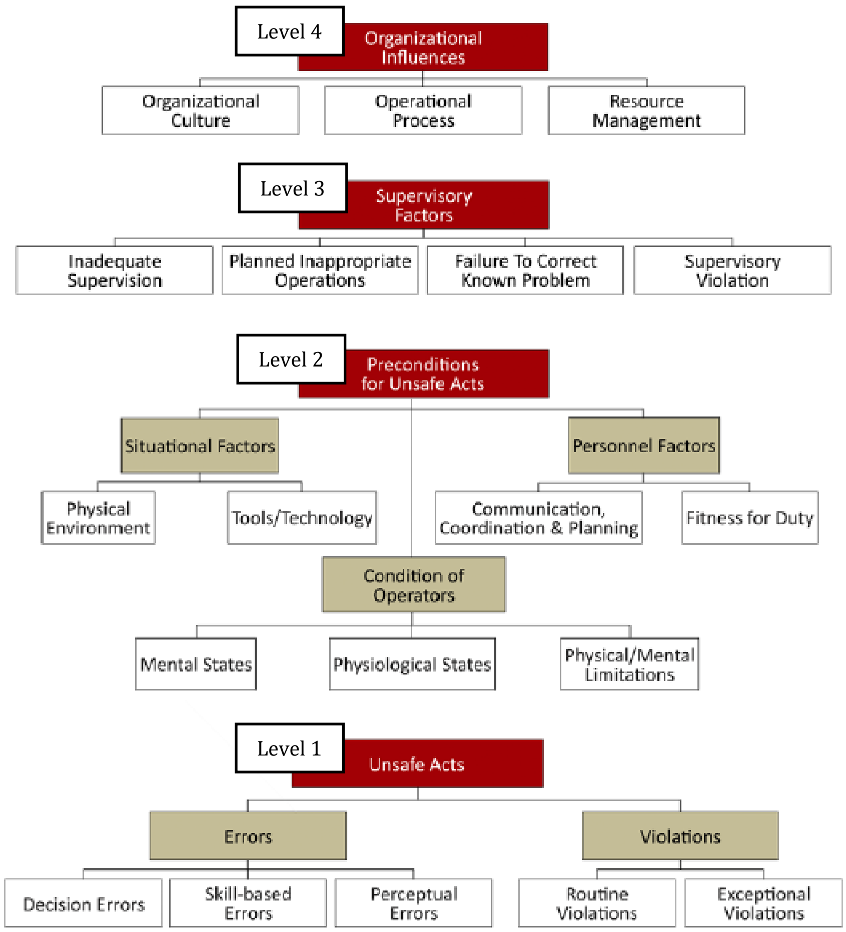

Fig. 1 *Human Factors Analysis and Classification System (HFACS) [15]*

According to [31], in the 1990s, professionals employed a systematic organisational approach to investigate aviation mishaps and establish mitigation measures. Furthermore, the HFACS model is believed to analyse and classify pilot errors in naval flying accidents and incidents. According to [32], this approach is also a prominent cause of accidents that can help to determine the link between active employee failure and latent variables, which is not always straightforward. When a human factor is involved in an accident, two types of mistakes can occur: a dynamic error, which has a widespread and almost immediate effect, often resulting from violating standard working protocols or using the wrong rules; and a latent error, which remains inactive for a while but becomes apparent when other factors are considered. Additionally, the HFACS framework has several taxonomic categories that indicate the level in the system where mistakes occurred [33].

3. Research Methodology

3.1 Research Design

This research employed a qualitative method with purposive sampling. Inclusion criteria for respondents are maintenance workers who have experienced incidents during working hours, and participation is voluntary. A total of five maintenance workers had volunteered to be interviewed. Apart from that, a secondary data review of the company's accident and incident reports was employed to fulfil the purpose of this research. The document had been requested during the engagement phase with the company. Once official approval was granted, the data collection phase was conducted.

3.2 Instrumentation

The Human Factors Analysis and Classification System (HFACS) is a general human error framework originally developed and tested as an approach to investigating and analysing the human causes of accidents with applications to rail, air, and offshore environments [34]. The Human Factor Analysis and Classification System (HFACS) encompasses the full range of system errors, from the sharp end (e.g., operators) to the blunt end (e.g., management). It derives from four levels of failure, namely unsafe acts, preconditions for unsafe acts, supervision factors, and organizational influences [15], [35]. The HFACS can be used to determine the impact of intervention strategies on overall accident rate and on specific types of human error that result in accidents or incidents over time [15]. Originally designed for aviation accident and incident analysis, the approach has also been adapted to investigate railway accidents, known as Human Factors Analysis and Classification System – Railway Accidents or HFACS-RA [4], [26], [36]. Instead of adopting the HFACS-RA framework, this research intentionally employed the original HFACS because the model has been extensively validated across high-risk domains, including aviation, maritime, and construction, and offers a well-established taxonomy with proven reliability. Given the exploratory and qualitative nature of the research design, the broader HFACS framework was deemed more appropriate for identifying and classifying general and latent human errors without being constrained by rail-specific adaptations. However, the findings were cross-referenced with railway-specific literature and established safety practices to ensure accuracy and contextual relevance within the HFACS framework.

3.3 Data Collection

The accident and incident reports were provided by the company. The data, consisting of 14 cases, were obtained from 2017 to 2021. Once reviewed, the data collection was continued with the interview session. The interview session was conducted online via Microsoft Teams. A set of structured questions was asked according to the HFACS domains, and the questions in this section were adapted from [35], [37]. The causes of accidents and incidents were systematically identified and categorised into the HFACS nanocodes. The HFACS domains consist of four primary sections, namely Unsafe Actions, Preconditions for Unsafe Acts, Supervisory Factors, and Organisational Influence, which were examined through qualitative feedback obtained from interviews.

3.4 Data Analysis

The HFACS standard tool was applied to data obtained from interviews. Dominant human factors were analysed through frequency distribution analysis and consequently classified according to HFACS nanocodes.

4. Results and Discussions

4.1 Human Factors Contributed to the Accident Based on the Reports

Based on the analysis of fourteen accident and incident reports provided by the company, covering the period from 2017 to 2021, only two HFACS levels were involved in the documented cases, as illustrated in Table 1. Among these, skill-based errors emerged as the most prominent category under unsafe acts, accounting for four out of fourteen cases (28.6%). These errors were unintentional, typically resulting from lapses in attention due to internal or external distractions. Internal contributors included excessive work pressure leading to reduced concentration, while external factors comprised environmental distractions such as noise or poor working conditions.

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The incidents can be broadly classified into three main categories. Among them, the physical environment was the most frequently cited factor, contributing to 50% of the cases. This highlights that hazardous physical conditions in the workplace represent the leading cause of worker injuries.

Additionally, tool or technology-related issues accounted for 7.1% of the incidents, primarily due to improper use of operational equipment. This suggests a gap in either training or adherence to standard safety working procedures.

In the context of railway maintenance operations, where tasks are complex and often collaborative, effective communication, coordination, and planning are essential. The analysis revealed that deficiencies in these areas contributed to two incidents, representing 14.3% of the cases. These findings underscore the importance of integrating structured team communication and operational planning into safety protocols for maintenance personnel.

Table 1 *HFACS levels and categories according to the accident/incident cases reported for the years 2017 to 2021*

HFACS levels and categories	Number of cases (n)	Percentage (%)
Level 1: Unsafe Act		
Decision Error	0	0
Skill-based Error	4	28.6
Perceptual Error	0	0
Routine Violation	0	0
Exceptional Violation	0	0
Level 2: Preconditions for Unsafe Acts		
Physical Environment	7	50
Tool/ Technology	1	7.1
Mental States	0	0
Physiological States	0	0
Physical/ Mental States	0	0
Communication, Coordination & Planning	2	14.3
Fitness for Duty	0	0
Total	**14**	**100**

4.2 Human Factors Contributed to the Accident and Incident Based on the Interview

Five maintenance workers from the same work section voluntarily participated in an interview session. The respondents' age distribution was as follows: the first respondent was between 51 and 60 years old; the second, between 41 and 50 years old; the third, between 21 and 30 years old; and the fourth and fifth, between 31 and 40 years old. Four respondents were married, while one was unmarried. The first and second respondents had extensive experience, each having served for over 21 years in the same organization. In contrast, the third respondent had less than five years of service. The fourth and fifth respondents reported service durations of 6 to 10 years and 11to 15 years, respectively. All participants had completed professional training through a certified institution and possessed comparable educational qualifications, including a Higher School Certificate, a diploma, or a bachelor's degree.

A majority of respondents (80%) attributed workplace accidents or injuries to unsafe acts (HFACS Level 1), particularly performance-based errors. Two respondents reported that accidents were caused by excessive or uncontrolled use of machinery or technology. Other participants indicated that procedural errors, such as performing tasks in the wrong sequence or neglecting to use standard checklists, were contributing factors. Furthermore, 80% of the respondents also identified errors in judgment and decision-making as critical causes of incidents. Three respondents specifically pointed to action-based errors during equipment operation, while one highlighted failure to assess risks associated with the work activity as the primary issue. Violations of established procedures were also prominent, with 60% of participants acknowledging that such procedural non-compliance led to their accidents.

Regarding preconditions for unsafe acts (HFACS Level 2), the analysis revealed several contributing categories, including physical environment, technological conditions, physical and mental states, sensory misperception, situational awareness, and team dynamics. Sixty percent of respondents cited the physical environment as a major cause, pointing to distractions or obstacles caused by equipment, confined workspaces, and poor lighting conditions. Another 60% linked accidents to mental states such as fatigue, stress, or cognitive overload. Additionally, 40% of participants attributed incidents to sensory misperception, where misreading instruments or misinterpreting machine signals led to errors. Disturbances in mental awareness caused by dark, cramped environments were also noted by 40% of respondents. Ineffective team communication was identified by 20% of participants as a teamwork-related factor contributing to their accidents.

Although supervisory factors (Level 3) were not prominently reported, some participants highlighted organisational influences (HFACS Level 4) as contributing to accident causation. Specifically, 20% reported challenges related to resource management, particularly the inadequacy of essential tools and machinery required for safe operations. These organisational shortcomings were perceived as direct contributors to unsafe conditions and increased accident risk.

Table 2 *HFACS levels and categories from interview analysis*

Respondents	HFACS- level			
	Unsafe Acts	Preconditions	Supervisory	Organisational Influence
1	1	1	-	-
2	-	1	-	-
3	1	-	-	-
4	1	1	-	-
5	1	1	-	1
Total	4 (80%)	4 (80%)	0 (0%)	1 (20%)

4.3 The HFACS Findings from the Reports and the Interview

The analysis of accident and incident reports (2017–2021) and responses from interviewed maintenance workers reveals a strong alignment in identifying key contributors to workplace accidents, particularly within the framework of HFACS Levels 1 and 2. Both results emphasise the predominance of unsafe acts, especially skill-based and performance-based errors, as central to accident causation. The documented reports show that 28.6% of incidents were linked to skill-based errors, often arising from distractions due to excessive workload or environmental stressors. Similarly, 80% of respondents attributed accidents to performance-related failures, such as improper equipment use or procedural errors, confirming the trend identified in the reports. Furthermore, both sources highlight the physical environment as a critical precondition, with 50% of documented cases and 60% of interviewees identifying poor lighting, confined spaces, and environmental hazards as major risks. These similarities demonstrate consistency between official documentation, which had been retrieved from the company's accident and incident reports, and worker experiences through the interview session, reinforcing the need to address environmental, cognitive, and procedural factors in accident prevention strategies.

Additionally, while the reports noted issues with communication, coordination and planning (14.3%), which indicate the surface level of accident causes, the interviews further expanded on the in-depth causes of the accidents. Mental states and team dynamics, such as fatigue, stress and ineffective communication, emerged as the root causes of the problem, hence pointing to an insight into complexity and a layered perspective of the human factors landscape. The findings signify the connection between human behaviour and psychology towards system operations.

Despite the less prominent supervisory factors and organisational influences in the report data, respondents did acknowledge gaps in resource management, highlighting the broader systemic issues that compound individual-level risks. This signifies that the interview facilitates a deeper understanding of accident causation, enabling precise identification of root causes, in this case focusing on management roles (HFACS level 4). This approach goes beyond merely addressing symptomatic factors, as identified in HFACS level 1 and HFACS level 2. Collectively, these findings validate the use of the HFACS model in diagnosing human error within the railway maintenance context and underscore the importance of integrated, multi-level safety interventions.

4.4 Discussions

Human factors play a pivotal role in understanding the root causes of workplace accidents, particularly in high-risk sectors like railways. At the broad level, skill-based and performance-based errors are critical contributors to such incidents, as they occur when individuals unintentionally deviate from expected actions, leading to adverse outcomes. Although these errors are not typically the result of deliberate violations, their consequences can be severe. As noted by [38], human error is defined as the failure to execute tasks as intended, thereby disrupting planned operations and may result in property or equipment damage. Maintenance errors, for instance, are often linked to inadequate maintenance practices, which exacerbate the probability of mistakes. Even routine

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maintenance tasks, despite their repetitive nature, carry inherent risks due to the potential for unintentional errors, especially in hazardous environments. Although the use of machines, standard procedures, and inspection checklists is designed to improve operational efficiency, these tools can also introduce challenges for maintenance personnel. Therefore, identifying the underlying causes of human error is essential for developing effective mitigation strategies.

Narrowing down to the empirical findings, interviews with maintenance workers who have experienced accidents reveal that both physical surroundings and mental states significantly influence the occurrence of incidents. Environmental factors such as weather conditions, fog, poor lighting, and general workplace discomfort were reported to impair visibility and mobility, thereby increasing the risk of errors [39]. In particular, confined and cluttered workspaces were found to hinder movement and situational awareness, further elevating the risk of accidents. These observations underscore the critical influence of the physical environment on workplace safety.

Mental states also emerge as significant contributors to workplace accidents. Fatigue, diminished alertness, and cognitive overload negatively affect workers' perception and task performance. According to [40], fatigue reduces functional capacity due to insufficient recovery from previous exertions, while [41] argues that prolonged work demands impair concentration. Mitigating fatigue requires coordinated efforts between employers and employees through the implementation of fatigue management, which may include ergonomic workplace design, fatigue awareness training, and optimised shift schedules [42]. In this research, respondents specifically noted that working night shifts in poorly lit conditions exacerbated attention lapses, highlighting the combined impact of environmental and psychological stressors.

To address such risks, workers reported adopting safety practices such as the use of personal protective equipment and team-based monitoring in confined environments. Communication among team members was also emphasised as a key element in maintaining operational safety. However, the persistence of unsafe acts, particularly those involving non-compliant behaviour with established procedures, still remains a concern. The research findings suggest that many incidents are rooted in either lapses of attention or behavioural deviations caused by external conditions, such as cramped spaces or poorly lit areas. These environmental triggers can encourage risky behaviours that conflict with standard safety protocols. [20] support this view by linking skill-based errors to operational stressors like fatigue and time pressure, thereby affirming the significance of both environmental and procedural factors in accident causation.

Although supervisory factors were not directly cited by respondents as a cause in the reported incidents, their role within the broader context of occupational safety and health management should not be overlooked. Effective supervision plays a pivotal role in enforcing compliance, allocating resources, and promoting a proactive safety culture. Some studies signify the disconnection between formal safety policies and supervisory practice, where supervisors focus on production over safety or underperform to fully engage with safety leadership, leading to diminished recognition of their safety role [43,44]. In sectors with high automation or centralised control systems, supervisors' active roles may be reduced or supplanted by technology, making their safety function less visible or recognised by workers [45,46]. However, the efficacy of supervisory factors is highly context-dependent. The style of leadership, sector, and organisational structure all play significant roles in determining whether supervisor interventions will be effective or counterproductive [43, 45].

From a safety risk management perspective, the findings affirm the practical value of the HFACS framework in systematically identifying the underlying causes of workplace accidents. The recognition of preconditions such as inadequate physical environments, mental fatigue, and sensory misperception provides actionable insights for risk mitigation. Addressing workplace distractions, enhancing lighting and ergonomic design, and managing workloads are some of the measures that can lead to meaningful improvements in occupational safety.

5. Conclusion

In conclusion, the findings revealed that unsafe acts, particularly skill-based errors, alongside poor physical environments and mental fatigue, were key contributors to incidents among railway maintenance workers. Thus, it signifies the importance of adopting a comprehensive approach to identifying root causes through human factor analysis and classification systems. By addressing these multifaceted contributors, which range from environmental conditions to fatigue management, organizations can develop human-centred safety interventions to systematically enhance workplace safety and reduce accident rates.

Beyond its empirical findings, this research offers significant contributions to both the railway industry and government policy. For industry, the HFACS framework enables structured identification of human error, supporting the development of safety interventions such as tailored training, fatigue risk management strategies and enhanced safety risk management to refine safety oversight. Furthermore, continuous improvement of the workplace physical environment and the implementation of customised safety training in the scope of cognitive ergonomics could be beneficial. These recommendations are particularly relevant for maintenance tasks that involve high operational complexity and environmental hazards. Hence, ensuring that safety measures apply to the dynamic and unique challenges faced by maintenance workers.

In the context of national priorities, the research focused on well-being, accountability and responsibility as well as innovation, in which these elements align with Malaysia MADANI principles. In addition, this research also supports the goals of the national OSH Master Plan 2021–2025 and the National Transport Policy 2019–2030 by creating a sustainable, resilient, and prosperous nation with environmentally friendly living conditions. Relevant authorities can utilise these insights to strengthen safety regulations, improve resource allocation, and incorporate human factors assessment into routine safety audits throughout the railway sector.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The roles of authors in carrying out this research are as follows: ***Conceptualisation and planning of the research, supervision, reviewing and editing the manuscript:*** *Rumaizah Ruslan;* ***Data collection, writing original draft, data analysis:*** *Nurfarizzatul Hana Zulkifle;* ***Reviewing, engagement with industry and validation:*** *Nor Aziati Abdul Hamid;* ***Reviewing and editing the final manuscript:*** *Nurrul Hafeezah Sahak;* ***Reviewing and editing the final manuscript:*** *Nurul Izzah Abdul Samad.*

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