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Risk Control Strategy for Mobile Crane through Active Safety Barrier Using PIR Sensor: A Literature Review

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Abstract

Introduction: *Mobile crane operations carry high accident risk in the line of fire zone, where workers face falling objects, load swing, and operator blind spots; national data show heavy-equipment accidents remain a significant contributor to occupational accidents, while control still relies on passive barriers dependent on worker compliance.* ***Objective:*** *This review examines theories and concepts underlying an active safety-barrier risk-control strategy using Passive Infrared (PIR) sensors in the line of fire zone of mobile crane operations.* ***Method:*** *A narrative literature review across nine themes: Hierarchy of Controls, Swiss Cheese Model, human error and human factors, ISO 31000:2018 risk management, mobile crane safety, the line of fire concept, the Bowtie method, passive-active safety barrier concepts, and PIR sensor technology.* ***Result and Discussion:*** *The nine themes are complementary and can be integrated into one theoretical framework, positioning the PIR sensor as an engineering control that closes latent and active gaps in the Swiss Cheese Model, mitigates human-factor limitations, and can be evaluated through ISO 31000 risk matrices and Bowtie diagrams before and after implementation.* ***Conclusion:*** *A PIR-based active safety barrier integrated with systemic risk management is potentially more reliable than administrative controls and PPE alone in reducing line of fire accident risk.*

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Introduction

Mobile cranes are among the most widely used lifting equipment in the construction, oil and gas, and mining industries because of their flexibility in moving materials under diverse field conditions, including confined work areas, uneven terrain, and locations that are difficult for fixed cranes (tower cranes or gantry cranes) to reach. The ability of mobile cranes to move from one work point to another without requiring permanent installation makes them the preferred choice for temporary or short-duration projects, such as steel structure erection, module lifting at oil and gas facilities, and loading-unloading activities in mining areas.

Behind its strategic role, the mobile crane is also classified as high-risk lifting equipment: even a small error at the planning, lifting, or supervision stage can lead to a fatal accident. Data from the Indonesian Ministry of Manpower's 2022 National Occupational Safety and Health Profile show that accidents involving heavy equipment, including cranes, remain a significant contributor to Indonesia's occupational accident rate and tend toward higher severity than accidents in general, given the greater energy involved in heavy-lifting operations (Adiratna et al., 2022). BPJS Ketenagakerjaan (2025) further recorded a persistent trend in such cases, indicating that current risk-control efforts have not been fully effective in reducing accident rates in high-risk work such as heavy-lifting-equipment operations.

One of the critical areas in mobile crane operations is the line of fire zone, namely the area where workers are potentially exposed to released energy or moving material, encompassing the area beneath the suspended load, the crane's swing radius, the operator's blind spot, and the crane's path of movement (International Association of Oil & Gas Producers, 2023). The area beneath the suspended load carries high risk because sling failure, hook failure, or rigging failure can cause the load to fall suddenly without prior warning, while the crane's swing radius is risky because the movement of the boom or the swinging load can sweep across the work area in a short time, far faster than a worker's reaction time to move away. The operator's blind spot, on the other hand, arises from the limited field of view from the operator's cabin over the surrounding area, particularly on large cranes with long boom configurations, so that the operator cannot always ensure the work area is truly clear of workers before lifting.

Struck-by accidents in this zone are often fatal given the limited reaction time available to workers and operators (Milazzo et al., 2015; Kim & Kang, 2022). Among the various categories of crane-related accidents Milazzo et al. (2015) identified—tipping, contact with electrical lines, structural failure, and rigging error among them—struck-by incidents are the most directly relevant here, as they involve direct interaction between workers and energy released from the lifting system. Kim and Kang's (2022) modified-MEPS analysis of fatal mobile crane accidents in South Korea further confirms that such accidents are rarely caused by a single factor, but instead involve complex interaction among human, equipment, procedural, and environmental factors, so effective control must target more than one failure point simultaneously.

Risk control in the line of fire zone has thus far relied mainly on passive barriers—signage, physical barricades, work procedures, and personal protective equipment (PPE)—which sit toward the lower, more human-dependent end of the broader hierarchy of workplace hazard controls (elimination, substitution, engineering controls, administrative controls, and PPE), rather than representing the full range of K3 control measures. Sobral and Guedes Soares (2019) argue that a barrier's reliability depends not merely on its existence but on its availability when needed, the consistency of its function over time, and its independence from other barriers; judged against these criteria, passive barriers remain fundamentally limited because their effectiveness depends entirely on workers' awareness and discipline, without an automatic mechanism to detect or prevent violations in real time—a constraint compounded by production-target pressures that often push workers and operators toward shortcuts.

National regulation of crane safety also remains general in nature: Minister of Manpower Regulation No. 8 of 2020 governs technical airworthiness—inspection requirements, operator certification, structural fitness—without provisions that explicitly require or encourage automatic sensor-based detection in high-risk zones such as the line of fire (Kementerian Ketenagakerjaan Republik Indonesia, 2020), a gap that may slow adoption of more advanced safety technology given companies' tendency to apply only minimum required standards. Advances in Passive Infrared (PIR) sensor technology, meanwhile, have been shown to improve occupational safety in other industrial settings through real-time human-presence detection that triggers alarm or shutdown systems without manual intervention (Welman Simatupang et al., 2020; Wibowo et al., 2021), and the technology is relatively inexpensive, easy to install, and already common in lighting-automation and security applications—making it a plausible candidate for adaptation to mobile equipment such as mobile cranes (Godase et al., 2025).

Studies on the Hierarchy of Controls, the Swiss Cheese Model, human factors, ISO 31000:2018, the Bowtie method, and PIR sensor technology have so far developed largely in isolation across domains such as patient safety, aviation, manufacturing, and food safety, with limited integration toward line of fire risk control in mobile crane operations specifically: the Hierarchy of Controls is applied broadly across sectors without elaborating sensor technology's place within it, the Swiss Cheese Model is used mainly in patient-safety and food-security incident analysis, and PIR sensor research remains largely confined to static production machinery rather than mobile equipment with a constantly changing danger zone. It is this gap that the present review addresses, offering a cross-disciplinary theoretical synthesis specific to a PIR-sensor-based active safety barrier for the line of fire zone—a contribution distinguishing this review from conventional reviews that typically discuss only a single theme in isolation.

This review was prepared to map and integrate the theories and concepts supporting a PIR-sensor-based active safety-barrier risk-control strategy in the line of fire zone of mobile crane operations, as a conceptual foundation for further occupational safety research and practice. It specifically addresses three questions: how the PIR sensor is theoretically positioned within the Hierarchy of Controls and Swiss Cheese Model frameworks; how the limitations of passive barriers can be explained through human error and human factors theory; and how the effectiveness of such an active safety barrier can be evaluated through the ISO 31000:2018 risk-management approach and the Bowtie method. These questions are addressed sequentially in the Results and Discussion section through nine interrelated sub-themes, before being synthesized into a single integrated theoretical and conceptual framework.

Method

This article is a narrative literature review, not a systematic review, prepared through four stages. First, source identification was conducted through the Scopus, ScienceDirect, SpringerLink, and Google Scholar databases, supplemented by international technical standards (ISO, ANSI/ASME), industry guidelines (IOGP Life-Saving Rules), and national laws and regulations (Indonesian Ministry of Manpower), using a combination of keywords: “mobile crane safety,” “line of fire,” “safety barrier,” “PIR sensor,” “Swiss Cheese Model,” “Bowtie method,” “human factors,” and “risk management ISO 31000.” Second, screening was carried out using inclusion criteria consisting of English- or Indonesian-language articles that directly discuss one of the nine review themes, prioritizing publications from 2015–2025, while articles that merely mention related terms without substantive discussion were excluded. Third, this process yielded 35 sources that were read in full text to ensure relevance, consisting of 28 scientific journal articles, 4 technical standards/guidelines (ISO 31000:2018, ASME B30.5, IOGP Life-Saving Rules, Minister of Manpower Regulation No. 8/2020), and 3 official government/industry reports (the Indonesian Ministry of Manpower's National OSH Profile, BPJS Ketenagakerjaan data, and internal Safe Zone Position documentation). Fourth, the relevant sources were thematically analyzed into nine main themes (Sections A–I of the Results and Discussion), which were subsequently synthesized narratively into a single integrated theoretical framework and conceptual framework (Section J). A limitation of this approach is its narrative nature, which does not apply a systematic protocol such as PRISMA, and is therefore not intended to claim exhaustive completeness, but rather to map and integrate key concepts that are conceptually relevant.

Result and Discussion

Hierarchy of Controls

The Hierarchy of Controls is a workplace hazard-control framework developed by the Occupational Safety and Health Administration (OSHA) and widely adopted by the National Institute for Occupational Safety and Health (NIOSH) to rank control strategies by effectiveness. It arranges five levels from most to least effective: elimination (removing the hazard entirely), substitution (replacing it with a lower-risk alternative), engineering controls (isolating people from the hazard through design, ventilation, physical barriers, or automation), administrative controls (changing how work is performed through procedures, training, and job rotation), and personal protective equipment (PPE) as the last layer.

Controls at higher levels are more reliable and less dependent on individual behavior than those at lower levels, so an optimal strategy generally combines several levels. Positioning a sensor-based active safety barrier as an engineering control is therefore relevant to the line of fire zone: it sits at the third level of the hierarchy, well above the administrative controls and PPE that still dominate current crane safety practice.

Swiss Cheese Model (Reason's Model)

The Swiss Cheese Model, developed by James Reason, explains how accidents occur in complex systems when failures penetrate multiple layers of organizational defense (Shabani et al., 2026). It portrays the safety system as a series of defensive layers—likened to slices of Swiss cheese—each containing holes or weaknesses; an accident occurs when the holes across layers align, allowing a hazard to penetrate the entire defense system (Karimi et al., 2021). The model comprises six interacting components: active failures—direct actions or decisions that can cause an accident, such as an operator failing to check sling condition or a rigger giving a mistaken signal (Raharjo et al., 2023; Jing et al., 2020); latent conditions—underlying organizational weaknesses, such as inadequate training programs or a safety-deprioritizing culture, that are not immediately visible but contribute to accidents over time (da Cunha et al., 2022; Larouzee & Le Coze, 2020); preconditions—factors such as time pressure, fatigue, and inadequate resources that increase the likelihood of active failure (Raharjo et al., 2023; Olson & Raz, 2021); unsafe acts—front-line errors and violations committed directly by the operator; defenses and barriers—preventive and mitigative measures such as safety protocols, pre-operation inspections, operator certification, lift plans, load moment indicators, work-zone restrictions, and operator-rigger communication procedures (Elsehrawy et al., 2021; Fu et al., 2020); and holes—the dynamic weaknesses in each layer arising from human error, equipment failure, inadequate training, or improper near-miss reporting (Gonzalez Barman, 2023; Karimi et al., 2021). This model is relevant to line of fire risk control because it explains the need for an additional independent layer of defense—here, an active safety barrier—so that a gap in one layer does not by itself result in an accident.

Human Error and Human Factors Theory

Human error is a leading cause of occupational accidents across sectors including mining and transportation (Gati et al., 2020). It is defined as a failure to correctly carry out an assigned task, potentially disrupting operations or causing an accident, and is classified into four forms (Tardeli et al., 2021): slips (execution errors in an otherwise correctly planned action), lapses (failure to remember necessary steps), mistakes (errors in planning or strategy selection), and violations (deliberate deviations from established procedure).

Tardeli et al.'s (2022) study of fatal mining accidents found human factors—fatigue, excessive workload, insufficient training, ineffective communication, poor working conditions, weak interface design, and time pressure—to be significant contributors, and the Human Factors Analysis and Classification System (HFACS), a Swiss-Cheese-Model-based framework, was developed to classify such errors across organizational levels (Datu et al., 2026). This confirms that operators, riggers, and workers in the line of fire zone remain vulnerable to slips, lapses, mistakes, and violations that procedure alone cannot eliminate, underscoring the need for an engineering control—such as sensor technology—that does not depend on human compliance.

Risk Management Theory (ISO 31000:2018)

ISO 31000:2018 (Risk Management – Guidelines) provides comprehensive guidance on the principles, framework, and process of risk management applicable across organization types and sectors. It defines risk as the effect of uncertainty on objectives—positive or negative—expressed through risk sources, potential events, consequences, and likelihood of occurrence (International Organization for Standardization, 2018). Key terms are summarized in Table 1.

Table 1
Key Terminology of ISO 31000:2018

Term	Definition
Risk	Effect of uncertainty on objectives; can be positive or negative
Risk management	Coordinated activities to direct and control an organization with regard to risk
Stakeholder	A person or organization that can affect, be affected by, or perceive itself to be affected by a decision or activity
Risk source	Something that alone or in combination has the intrinsic potential to give rise to risk

Term	Definition
Event	An occurrence or change in a particular set of circumstances that can be a source of risk
Consequence	The outcome of an event affecting objectives; can be positive or negative
Likelihood	The chance of something happening, whether qualitative or quantitative
Control	A measure that maintains and/or modifies risk

ISO 31000:2018 also establishes eight principles of risk management as the foundation for effective and efficient implementation, as summarized in Table 2.

Table 2

Eight Principles of ISO 31000:2018 Risk Management

Principle	Explanation
Integrated	Risk management is an integral part of all organizational activities, not a stand-alone function
Structured and comprehensive	A structured approach produces consistent and comparable results
Customized	The risk management structure and process are adapted to the organization's external and internal context
Inclusive	Timely stakeholder involvement allows their perceptions to be considered in decision-making
Dynamic	Risk management is able to anticipate, detect, and respond to changes in context appropriately
Best available information	Inputs are based on historical, current, and future expectation information, taking uncertainty into account
Human and cultural factors	Human behavior and culture significantly influence all aspects of risk management
Continual improvement	Risk management is continuously enhanced through organizational learning and experience

The risk management process—communication and consultation, establishing context and criteria, risk assessment, risk treatment, monitoring and review, and recording and reporting—is often presented sequentially but is applied iteratively at the strategic, operational, program, or project level. Risk analysis may be qualitative, quantitative, or a combination of both, considering likelihood, consequence, control effectiveness, and time; the risk matrix is a common tool for this, evaluating risk based on likelihood and consequence parameters. This framework provides the methodological reference for evaluating the change in occupational-accident risk in the line of fire zone before and after implementation of the active safety barrier.

Mobile Crane Operation Safety

As noted in the Introduction, the mobile crane is critical equipment in the construction and mining industries with substantial accident risk, with heavy-equipment accidents remaining a significant contributor to Indonesia's national occupational accident rate (Adiratna et al., 2022) and struck-by incidents forming the accident category most relevant to line of fire risk (Milazzo et al., 2015; Kim & Kang, 2022).

Beyond these direct causes, organizational, technical, and individual factors also contribute to fatal crane accidents (Melchior & Zanini, 2019), gender differences in lost workdays point to the relevance of demographic factors in safety-system design (Fontaneda et al., 2019), and safety leadership by field managers plays an important role in promoting—or impeding—safe practice (Grill & Nielsen, 2019). Implementation gaps persist even where standards exist, such as the American National Standards Institute's Mobile and Locomotive Cranes Safety Standard (ASME B30.5) (Im & Park, 2020), and

Indonesian regulation remains general, without specific provision for active safety-barrier technology (Kementerian Ketenagakerjaan Republik Indonesia, 2020)—leaving room for sensor-technology-based control strategies.

Line of Fire Concept

The International Association of Oil & Gas Producers (IOGP) defines the line of fire as the area in which a person can be injured by released energy or moving material—in mobile crane operations, encompassing the area beneath the suspended load, the swing radius, the operator's blind spot, the potential fall area of material or components, and the crane's path of movement (International Association of Oil & Gas Producers, 2023). The IOGP Life-Saving Rules require workers to stay clear of the line of fire, verify isolation before work begins, and use designated protective equipment as fundamental means of preventing fatal accidents.

Safe Zone Position (2022) documentation further explains the exclusion zone, physical barricade, and operator blind spot (scotoma)—the area around the crane the operator cannot directly see from the cabin, creating high risk for workers present there without the operator's awareness. This blind-spot characteristic is the main argument for an automatic sensor-based detection system that does not rely solely on the operator's vision.

Bowtie Method in Risk Analysis

The Bowtie method integrates fault tree analysis (causes) with event tree analysis (consequences) to produce an intuitive graphical visualization of the relationships among hazard, threats, top event, consequences, and barriers (Alizadeh & Moshashaei, 2015). A Bowtie diagram comprises a hazard (the potential source of danger, e.g., a suspended load), threats (factors that can develop the hazard into a top event), a top event (the undesired occurrence, e.g., a dropped load), consequences (impacts of the top event), preventive barriers (controls preventing threats from developing into the top event), and mitigative barriers (controls limiting impact after the top event occurs).

De Ruijter and Guldenmund (2015) found the Bowtie method widely applied across high-risk industries—oil and gas, chemicals, aviation, construction—for its ability to communicate complex risks clearly to stakeholders. Cheraghi et al. (2019) showed that integrating quantitative methods with a bowtie-like approach, as in their Fuzzy Multi-Attribute HAZOP Technique (FMA-HAZOP) for gas wellhead facilities, can further improve risk-assessment accuracy, while Sobral and Guedes Soares (2019) emphasize evaluating barriers not just by their existence but by their availability, reliability, effectiveness, independence, and auditability. The Bowtie method is thus relevant for comparing the line of fire risk profile before and after implementation of a PIR-sensor-based active safety barrier.

Safety Barrier: Passive and Active Concepts

A passive safety barrier is a control that functions without external energy or an active response (Sobral & Guedes Soares, 2019), encompassing warning signs, physical barriers, work procedures and permit-to-work systems, operator training, PPE, and engineering features such as limit switches and load moment indicators. Its main weakness is high dependence on worker compliance, making it prone to failure under human error, violations, or abnormal conditions.

An active safety barrier, by contrast, proactively detects hazardous conditions and responds automatically to prevent or mitigate risk, characterized by real-time detection and monitoring, automatic response, integration with control systems, continuous verification, and feedback. Fang et al. (2016) developed a real-time proactive safety-assistance framework for mobile crane lifting that integrates multiple sensors to warn and guide operators; Welman Simatupang et al. (2020) and Wibowo et al. (2021) applied PIR sensors to improve worker safety on industrial production machinery by detecting human presence through infrared radiation to trigger an alarm or shutdown; and Awad et al. (2026) demonstrated cost-effective IoT-based sensors for monitoring harbor cranes.

A variety of sensor types are relevant to crane safety barriers, including proximity sensors (distance to a hazardous zone), PIR sensors (worker presence), ultrasonic sensors (ranging and obstacle detection), RFID/BLE tags (personnel tracking), camera-based vision systems with artificial intelligence, load cells (actual load monitoring), and inclinometers (crane tilt and stability).

Passive Infrared (PIR) Sensor Technology for Safety Barrier Systems

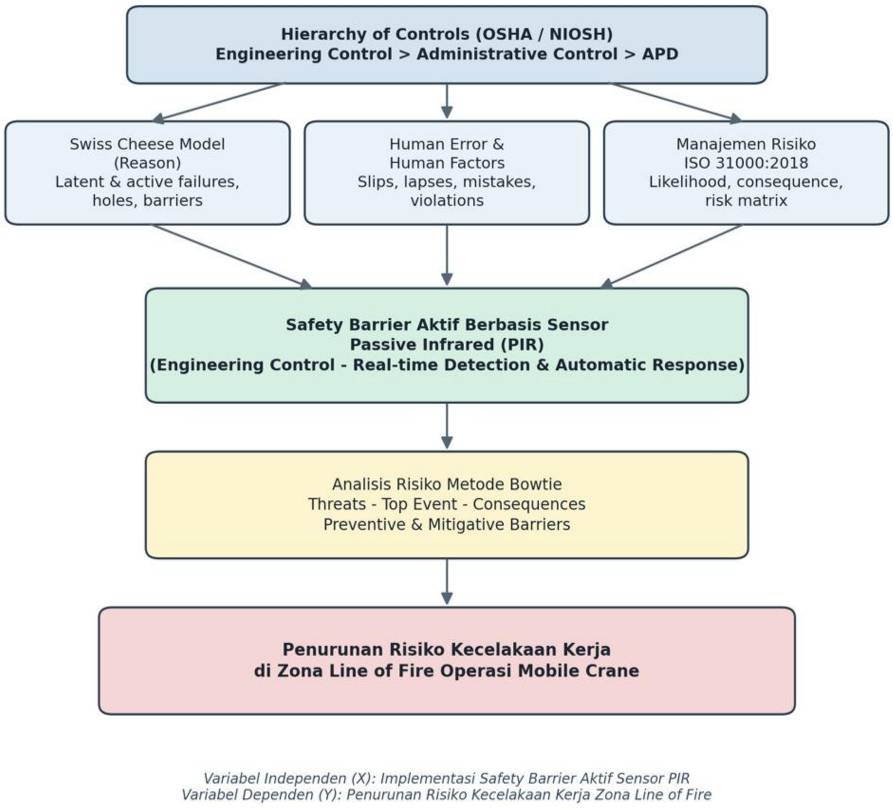
PIR sensor technology detects infrared radiation emitted by moving objects—particularly human or animal body heat—and triggers a pre-programmed response when movement occurs within its detection range (Godase et al., 2025). Compared with manually controlled systems, PIR sensors are simple and cost-effective, operating autonomously after installation to detect movement and manage occupancy-based responses in real time, with high adaptability across residential to industrial settings, low cost, easy installation, minimal maintenance, a long service life, and a delay mechanism to avoid false triggers from minor movement or environmental factors such as wind.

A PIR safety-automation system comprises a sensor that detects infrared radiation and sends a voltage signal, a transistor that amplifies the signal, a relay module that switches higher voltage or current, and an output device—an alarm or warning system—activated on detection. Integrating Internet of Things (IoT) technology adds remote monitoring and control via smartphone, tablet, or computer, including sensitivity adjustment and movement notifications.

In mobile crane safety, PIR sensors can serve as an active safety barrier detecting personnel presence in real time in the line of fire zone, triggering automatic visual/audio warnings, integrating with the crane control system for preventive action, and enabling remote monitoring by operators and safety officers. Challenges include sensitivity to environmental conditions and potential false triggers, requiring precise sensor placement, configuration suited to site characteristics, a multi-sensor approach, and periodic calibration and maintenance. Overall, a PIR-sensor-based system supports a hierarchical control strategy by providing an engineering-control layer that reduces reliance on administrative controls and PPE alone.

Synthesis of the Theoretical Framework and Conceptual Framework

Based on the nine themes reviewed, an integrated theoretical framework positions the Hierarchy of Controls (OSHA/NIOSH) as the foundation for placing a PIR-sensor-based active safety barrier as an engineering control at the third level of the hierarchy, above administrative controls and PPE. The Swiss Cheese Model justifies why an added active defensive layer is crucial, since each independent layer closes gaps that latent or active failures could otherwise exploit. Human error and human factors theory explain why passive barriers alone are inadequate, since operators, riggers, and workers in the line of fire zone remain vulnerable to slips, lapses, mistakes, and violations that procedure cannot fully eliminate—positioning PIR sensor technology as an engineering control independent of human compliance. This theoretical construction is then operationalized through the Bowtie method, which enables structured evaluation of threats, preventive barriers, and consequences before and after implementation, complemented by the risk matrix consistent with ISO 31000:2018 principles; the risk matrix and Bowtie diagram on their own provide a structured qualitative or semi-quantitative comparison rather than an automatic quantitative measurement, so translating the before-after change into fully quantitative metrics would require supplementary statistical or quantitative methods (Alizadeh & Moshashaei, 2015; de Ruijter & Guldenmund, 2015). Picture 1 illustrates this integration, and Table 3 summarizes each theme's contribution to the overall framework.



Picture 1. Integrated Theoretical Framework of a PIR-Sensor-Based Active Safety Barrier

Table 3
Summary of the Literature Map and Its Contribution to the Research Framework

No	Theme/Concept	Key Source	Contribution to the Research Framework
1	Hierarchy of Controls	OSHA; NIOSH	Positions the active safety barrier as an engineering control
2	Swiss Cheese Model	Shabani et al. (2026); Karimi et al. (2021)	Explains the need for an additional independent defensive layer
3	Human Error & Human Factors	Gati et al. (2020); Tardeli et al. (2021, 2022)	Explains the limitations of barriers that depend on humans
4	ISO 31000:2018 Risk Management	International Organization for Standardization (2018)	Provides a risk assessment and measurement framework
5	Mobile Crane Operation Safety	Kim & Kang (2022); Milazzo et al. (2015)	Maps the types and causes of crane accidents
6	Line of Fire Concept	IOGP (2023); Safe Zone Position (2022)	Defines the area and characteristics of the risk zone
7	Bowtie Method	Alizadeh & Moshashaei (2015); de Ruijter & Guldenmund (2015)	Provides a before-after risk evaluation tool for implementation
8	Passive-Active Safety Barrier	Sobral & Guedes Soares (2019); Fang et al. (2016)	Distinguishes barrier characteristics and evaluation criteria
9	PIR Sensor Technology	Godase et al. (2025); Welman Simatupang et al. (2020)	Serves as the core technology of the proposed active safety barrier

It should be critically noted that the majority of the studies underlying the synthesis above originate from application domains outside mobile crane operations directly: the Swiss Cheese Model and its indicator development have mostly been tested in the patient-safety and food-security sectors (da Cunha et al., 2022; Elsehrawy et al., 2021; Karimi et al., 2021), while research on sensor-based active safety barriers has been validated more on stationary industrial production machinery (Welman Simatupang et al., 2020; Wibowo et al., 2021) rather than in a dynamic work environment such as the moving and constantly changing line of fire zone of a crane. This condition indicates a contextual transfer gap: the theoretical effectiveness of the nine themes may not necessarily hold fully without empirical testing under actual mobile crane field conditions, given the differences in risk characteristics, detection-area scale, and environmental conditions (vibration, distance, weather) that are more extreme than in the original contexts of these studies. Therefore, the theoretical framework in Picture 1 should be positioned as a conceptual hypothesis requiring empirical field validation, rather than as a conclusion already proven in the mobile crane context.

The theoretical framework is then derived into a research conceptual framework that describes the causal relationship between independent and dependent variables in the context of mobile crane operation risk control. The independent variable (X) in this framework is the implementation of a PIR-sensor-based active safety barrier, which includes sensor installation in the line of fire zone, a real-time audio alarm system, risk analysis using the Bowtie Model, and an integrated control strategy comprising SOPs and PPE. The dependent variable (Y) is the reduction in occupational-accident risk in the line of fire zone of mobile crane operations. The conceptual relationship established indicates that effective implementation of an active safety barrier — through the application of PIR sensors, Bowtie Model risk analysis, and an integrated risk-control approach — will reduce both the probability and the severity of occupational accidents in the line of fire zone.

Conclusion

This literature review shows that a risk-control strategy for the line of fire zone in mobile crane operations depends on a comprehensive theoretical framework encompassing the Hierarchy of Controls, the Swiss Cheese Model, human error and human factors theory, ISO 31000:2018 risk management, mobile crane safety characteristics, the line of fire concept, the Bowtie method, the passive-active safety barrier concept, and PIR sensor technology. Integrating these nine themes produces a strong theoretical argument that positioning the PIR sensor as an active engineering control can close the defensive gaps long inherent in administrative controls and PPE, while also providing a structured, before-and-after basis for evaluating that risk reduction through risk matrices and Bowtie diagrams—though translating this evaluation into fully quantitative metrics would require supplementary quantitative or statistical methods beyond what these tools provide on their own.

The resulting conceptual framework—with the implementation of a PIR-sensor-based active safety barrier as the independent variable and the reduction of occupational-accident risk in the line of fire zone as the dependent variable—can serve as a reference for further empirical research, including system-design testing, evaluation of the change in risk level before and after implementation, and cost-benefit analysis of applying this technology to mobile crane operations in the field. This framework is conceptual, built from a cross-domain synthesis largely untested directly in the mobile crane context, so empirical field validation is a prerequisite before it is applied or generalized. Further studies are recommended to validate it empirically across industrial contexts, strengthening the generalizability of findings and supporting the refinement of heavy-lifting-equipment safety regulations in Indonesia.

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