INTISARI

Keselamatan dan kesehatan kerja (K3) pada operasi mobile crane menjadi perhatian serius mengingat tingginya angka kecelakaan fatal yang berkaitan dengan zona line of fire, yaitu area di mana pekerja berpotensi terpapar energi atau material yang bergerak. Pengendalian risiko tradisional yang bersifat pasif, seperti rambu peringatan dan prosedur kerja, terbukti kurang efektif dalam mencegah kecelakaan, terutama akibat human error dan kondisi operasional yang dinamis. Penelitian ini bertujuan merancang dan mengimplementasikan strategi pengendalian risiko operasi mobile crane melalui safety barrier aktif berbasis sensor passive infrared (PIR) pada zona line of fire dengan pendekatan Bowtie Model untuk menurunkan probabilitas dan tingkat severity kecelakaan kerja. Penelitian menggunakan pendekatan project-based applied research dengan jenis deskriptif kualitatif yang didukung data kuantitatif sekunder, dilaksanakan di PT. BHI Kabupaten Bengkalis, Riau selama periode Januari–April 2026. Pengumpulan data dilakukan melalui observasi lapangan, wawancara, kuesioner user acceptance testing (UAT), dan telaah dokumen, kemudian dianalisis menggunakan bowtie model, matriks risiko, serta analisis biaya-manfaat (cost-benefit analysis). Hasil penelitian mengidentifikasi tujuh titik eksposur kritis zona line of fire (Z-1 hingga Z-7) yang selanjutnya dipasangi sensor PIR pada batas yellow zone. Sistem yang dirancang mencapai akurasi deteksi 95% dengan waktu respons rata-rata 0,8 detik dan jarak aman deteksi 2,15 meter yang memenuhi standar ISO 13855:2024, serta memperoleh tingkat penerimaan pengguna sebesar 96% (skor UAT 4,80 dari 5,00). Diagram Bowtie Model pasca-implementasi menunjukkan penambahan tiga lapisan active barrier independen (deteksi sensor PIR, alarm audio-visual otomatis, dan remote monitoring safety officer) yang mengubah karakter pengendalian risiko dari administrative-passive menjadi engineering-active. Analisis matriks risiko menunjukkan penurunan tingkat risiko pada seluruh titik eksposur, dari kategori High Risk (level 16) menjadi Low Risk (level 4) pada lima titik (Z-1, Z-2, Z-3, Z-6, dan Z-7) dan Medium Risk (level 6) pada dua titik (Z-4 dan Z-5). Analisis biaya-manfaat pada skenario pencegahan satu kecelakaan fatal per tahun menghasilkan nilai Benefit-Cost Ratio sebesar 45,6:1 dan Return on Safety Investment sebesar 4.462% dengan titik impas 0,022 kecelakaan/tahun; pada skenario konservatif pencegahan satu kecelakaan cedera berat per tahun tetap diperoleh BCR 19,2 : 1, ROSI 1.820%, dan titik impas 0,052 kecelakaan/tahun, yang menunjukkan kelayakan ekonomis yang sangat tinggi dan tidak bergantung pada asumsi tingkat keparahan kecelakaan yang berhasil dicegah. Penelitian ini menyimpulkan bahwa strategi pengendalian risiko berbasis integrasi Bowtie Model dan safety barrier aktif sensor PIR, dengan formula geometri deteksi sensor sebagai unsur novelty penelitian ini, efektif sebagai engineering control yang mengubah paradigma pengendalian risiko K3 pada operasi mobile crane dari administratif-pasif menjadi rekayasa-aktif, teruji secara teknis, penerimaan pengguna, dan kelayakan ekonomis. Hasil ini direkomendasikan untuk diintegrasikan secara permanen ke dalam SOP PT. BHI dan perusahaan minyak dan gas sejenis, diadopsi sebagai best practice industri, serta dijadikan masukan bagi regulator dalam pembaruan Permenaker No. 8 Tahun 2020 dan penyusunan SNI safety barrier aktif pada operasi mobile crane.

Kata kunci: *line of fire, mobile crane, safety barrier aktif, sensor passive infrared, Bowtie Model, matriks risiko..*

ABSTRACT

Occupational safety and health (OSH) in mobile crane operations remains a serious concern given the high rate of fatal accidents associated with the line of fire zone, an area in which workers are potentially exposed to moving energy or materials. Conventional passive risk controls, such as warning signs and work procedures, have proven insufficiently effective in preventing accidents, particularly those caused by human error and dynamic operational conditions. This study aimed to design and implement a risk control strategy for mobile crane operations through an active safety barrier based on passive infrared (PIR) sensors in the line of fire zone, employing a Bowtie Model approach to reduce both the probability and severity of occupational accidents. The study used a project-based applied research approach with a qualitative descriptive design supported by secondary quantitative data, conducted at PT. BHI, Bengkalis Regency, Riau, over the period of January–April 2026. Data were collected through field observation, interviews, user acceptance testing (UAT) questionnaires, and document review, then analyzed using the bowtie model, risk matrix, and cost-benefit analysis. The results identified seven critical exposure points within the line of fire zone (Z-1 to Z-7), at which PIR sensors were subsequently installed along the yellow zone boundary. The designed system achieved a detection accuracy of 95% with an average response time of 0.8 seconds and a safe detection distance of 2.15 meters, meeting the ISO 13855:2024 requirement, and obtained a 96% user acceptance rate (UAT score of 4.80 out of 5.00). The post-implementation bowtie model diagram revealed the addition of three independent active barrier layers (PIR sensor detection, an automatic audio-visual alarm, and remote monitoring by the safety officer), transforming the character of risk control from administrative-passive to engineering-active. Risk matrix analysis showed a significant risk reduction across all exposure points, from High Risk (level 16) to Low Risk (level 4) at five points (Z-1, Z-2, Z-3, Z-6, and Z-7) and Medium Risk (level 6) at two points (Z-4 and Z-5). The cost-benefit analysis yielded a Benefit-Cost Ratio of 45.6:1 and a Return on Safety Investment of 4,462% under the scenario of preventing one fatal accident per year, with a break-even point of 0.022 accidents/year; under the more conservative scenario of preventing one serious-injury accident per year, the system remained feasible with a BCR of 19.2:1, an ROSI of 1,820%, and a break-even point of 0.052 accidents/year, indicating very high economic feasibility that does not depend on assumptions about the severity of the accident prevented. The study concludes that the risk control strategy integrating the Bowtie Model with a PIR sensor-based active safety barrier, supported by the sensor detection geometry formula as this study's novel contribution, is effective as an engineering control that shifts the OSH risk-control paradigm in mobile crane operations from administrative-passive to engineering-active, as validated technically, in user acceptance, and in economic feasibility. These findings are recommended for permanent integration into the SOPs of PT. BHI and similar oil and gas companies, adoption as an industry best practice, and use as input for regulators in updating Manpower Ministerial Regulation No. 8 of 2020 and developing an Indonesian National Standard (SNI) for active safety barriers in mobile crane operations.

Keywords: *line of fire, mobile crane, active safety barrier, passive infrared sensor, Bowtie Model, risk matrix.*