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SAFETY RISK CLASSIFICATION OF A MARBLE GANG SAW MACHINE USING FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

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Abstract: Failure Mode and Effects Analysis (FMEA) was applied to a gang saw machine operating in a marble processing facility in the Aegean Region of Türkiye, where 74 personnel work under a two-shift production system. The analysis aimed to identify and prioritize occupational safety risks associated with the cutting line under actual operating conditions**, focusing on a single high risk production machine rather than on a plant wide assessment. Based on expert evaluations, maintenance and breakdown records, occupational accident documentation, near miss reports and field observations, 26 potential failure modes were identified. Each failure mode was evaluated using Occurrence, Severity and Detectability parameters scored on a 1–10 scale and Risk Priority Numbers were calculated accordingly. Initial RPN values ranged from 162 to 294. The highest risk levels were associated with blade tension imbalance (294), blade fracture (288), operator intervention with guards open (288) and insufficient block fixation (280). Elevated RPN values were also observed for vibration exposure, noise exposure and slurry related slip hazards. Following the implementation of engineering controls, preventive maintenance improvements and reinforced operational procedures, recalculated RPN values decreased substantially, with all evaluated failure modes reduced below the immediate action threshold of 100. On average, the Risk Priority Number fell from 226.2 to 50.3, corresponding to an overall reduction of approximately 77.7 %. The results suggest that systematic machine level risk assessment provides a practical framework for strengthening occupational safety performance in marble processing facilities** and that the corrective logic identified here is transferable to comparable stone cutting equipment.

Keywords: Failure mode and effects analysis, Gang saw machine, Marble processing, Occupational health and safety in mines

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1. Introduction

Türkiye is one of the leading producers in the global natural stone industry, supported by extensive marble reserves and a mature industrial processing capacity developed over decades. The country holds a significant share of the international marble market, with large reserve concentrations in provinces such as Afyonkarahisar, Denizli, Muğla and Bilecik (Erkanol and Aydındağ, 2013; Adıgüzel, 2019). The sector operates through a widespread network of quarries and processing plants and provides substantial employment within industrial regions. This production capacity places marble processing facilities among the principal heavy manufacturing environments in the country.

Despite its economic importance, marble processing remains classified as a highly hazardous industrial activity due to the mechanical, physical and operational risks involved. Block handling, slab cutting, polishing operations and material transportation expose workers to crushing hazards, falling materials, excessive vibration and elevated noise levels (Önder et al., 2022; Dolmaz and Bentli, 2024). In several facilities, noise levels have been reported to exceed 120 dB, while prolonged vibration exposure and inadequate dust control have been associated with occupational disorders. Previous risk analyses conducted using methods such as Fine Kinney indicate that cutting lines and lifting operations constitute some of the highest risk zones within marble plants (Demir and Eker, 2025). Human related factors, including unsafe machine intervention and insufficient use of protective equipment, further increase accident probability (Çetin, 2003; Şahin and Eker, 2024).

Among the production units, the gang saw machine represents the core equipment in slab manufacturing. This multi blade cutting system transforms large marble blocks into thin slabs through a reciprocating mechanical mechanism. Modern gang saw machines utilize rigid frames, hydrostatic linear guides and diamond segmented blades to achieve dimensional accuracy and high material efficiency (Gürbulak, 2007; MKS Makina, 2022). The ability to cut at thicknesses of approximately 1.8–2 mm increases yield and reduces material loss during processing. However, the dynamic motion of the blade

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assembly, combined with the substantial mass of marble blocks, generates a complex risk profile involving mechanical imbalance, structural instability, hydraulic failures and unsafe operator interaction. Because these hazards are concentrated at a single, continuously operating unit, the gang saw constitutes one of the most safety critical points along the entire processing line, yet it is rarely examined as an independent unit of analysis.

Occupational health and safety studies in the marble industry predominantly focus on facility wide risk assessments. Methods such as Fine Kinney, HAZOP and related qualitative approaches have been widely applied to evaluate general workplace hazards including dust exposure, noise, manual handling and machinery related injuries (Eyüboğlu and Özfırat, 2025). While these studies provide valuable insights into plant level safety management, detailed and systematic analyses centered on a single critical production machine remain limited. Plant wide assessments necessarily aggregate hazards across many different operations, which tends to dilute the visibility of machine specific failure mechanisms—such as blade tension imbalance, trolley lifting asymmetry, or dynamic instability during reciprocating motion—that do not emerge clearly at the facility scale. Moreover, the limited research directly addressing gang saw machines has largely concentrated on cutting performance and equipment effectiveness rather than occupational safety; Varol (2024), for instance, reports the absence of machine level effectiveness studies for stone cutting equipment, pointing to a comparable gap on the safety side. Machine specific evaluation is particularly important for gang saw systems due to their continuous operation, mechanical complexity and direct interaction with operators during block positioning and cutting adjustments (Gul and Ak, 2021).

Failure Mode and Effects Analysis (FMEA) is a structured and preventive risk assessment method designed to identify potential failure modes, evaluate their causes and consequences and prioritize corrective measures. The method has been extensively applied in mining, manufacturing and high-risk industrial systems for proactive safety management. By quantifying risk through Occurrence, Severity and Detectability parameters, FMEA enables systematic comparison of failure modes and supports targeted intervention planning (Ersoy et al., 2017; Kasap and Sırakaya, 2019). More recent research has sought to overcome well known limitations of the classical approach—particularly the subjectivity of expert scoring and the assumption that Occurrence, Severity and Detectability carry equal weight—by integrating FMEA with fuzzy logic and multi criteria decision making (MCDM) techniques (Toptancı et al., 2025; Gao and Zhou, 2025). Despite both its widespread application across sectors and these methodological advances, equipment level FMEA implementations targeting an individual machine within marble processing lines remain scarce.

The primary objective of this study is to conduct a systematic Failure Mode and Effects Analysis of a gang saw machine operating in a marble processing facility. The study aims to identify machine related failure modes, quantify associated occupational risks and prioritize corrective actions based on Risk Priority Number calculations. By focusing on a single high impact production unit, the research seeks to provide a structured and technically grounded risk evaluation approach applicable to heavy stone cutting operations. The novelty of the study lies in shifting the unit of analysis from the plant to a single high-risk machine and in quantifying the effectiveness of the proposed corrective actions through a before and after comparison of Risk Priority Numbers under actual operating conditions. In doing so, it contributes a transferable machine level risk assessment framework that complements the predominantly plant wide FMEA literature in the marble sector.

2. Materials and Methods

2.1. Description of the Study Area

This study was conducted in a medium sized marble processing plant located in the Aegean Region of Türkiye. The facility operates as an integrated production system in which marble blocks extracted from quarries are processed into slabs and subsequently subjected to surface finishing operations. The plant employs a total of 74 workers. Among them, 18 are assigned to the block cutting line, 12 to surface processing and polishing operations, 9 to maintenance and technical services, 6 to quality control and laboratory units and the remaining personnel work in logistics, stock management and administrative departments. The facility is classified as highly hazardous due to continuous machine operation, heavy block handling activities and the use of lifting equipment with substantial load carrying capacity.

The annual block processing capacity of the plant is approximately 48.000 m3, corresponding to an average monthly processing volume of about 4.000 m3. Production is carried out in a two shifts production system. The first shift operates between 08.00 and 16.00 and the second shift operates between 16.00 and 24.00. Scheduled maintenance activities are performed during weekly planned shutdown periods, while major maintenance interventions are conducted within quarterly maintenance plans. The plant layout consists of a block storage yard, cutting line, slab storage area, wastewater treatment unit and administrative building. The general layout of the facility and the configuration of the production areas are presented in Figure 1.

The gang saw examined in this study is located at the center of the cutting line and functions as the main cutting unit of the facility. It operates with an 80-blade configuration driven by a main motor rated at 110 kilowatts. The cutting stroke reaches 3.2 meters, while the maximum block height and width are 2.1 meters and 2.0 meters, respectively. The machine frame is constructed from high rigidity steel and runs on a hydrostatic linear bearing system, which helps limit vibration and supports

dimensional consistency during slab production. The hydraulic system operates at an average pressure of 180 bar to ensure block lifting and stabilization. Heat generated during cutting is controlled through a water circulation system, while slurry removal is achieved by means of discharge channels and pump units integrated into the base structure. The actual gang saw machine installed in the facility is presented in Figure 2. Considering its structural configuration and its decisive role in slab production, this equipment was selected as the primary analysis unit of the study. Its mechanical motion components, hydraulic stabilization system and continuous cutting operation generate a complex risk profile that includes mechanical, hydraulic and operator related hazards requiring systematic evaluation through the FMEA method.



Figure 1. General view of the marble processing plant.



Figure 2. Gang saw machine installed in the cutting line of the facility.

2.2. Operational Process of the Gang Saw Machine

The gang saw machine transforms large marble blocks into thin slabs through a multi blade cutting system operating in a reciprocating frame mechanism. The system typically consists of 60 to 120 parallel diamond coated blades mounted on a rigid frame that moves linearly through motion transmitted by a flywheel and connecting rod assembly supported by hydrostatic guides. This mechanical transmission system, including the flywheel, connecting rods, blade frame assembly and trolley lifting mechanism, is illustrated in Figure 3.

The operational process begins with block placement and preparation. Marble blocks are unloaded into the cutting area by means of a gantry crane. Surface dressing is performed to remove irregularities and visible defects. For structural stability, fiberglass mesh and resin may be applied to block surfaces prior to cutting. The prepared block is then positioned onto a hydraulic elevator trolley and aligned through mechanical guides or laser positioning systems to ensure correct orientation within the cutting frame (Engin et al., 2019).

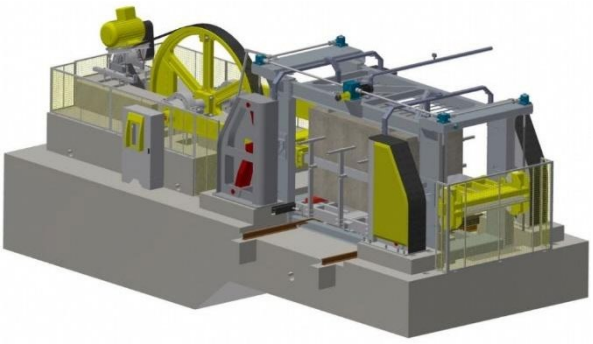


Figure 3. Technical view of the gang saw machine (MKS Makina, 2026).

Following placement, the block is fixed securely on the trolley. Hydraulic side presses are activated to prevent lateral displacement and wooden wedges combined with gypsum are used when angular stabilization is required to ensure cutting stability (Öz and Özkan, 2025; Şahin and Eker, 2024). Cutting parameters are then defined through a programmable logic controller interface. Operators enter block dimensions, cutting stroke values typically between 50 and 80 centimeters, feed rate, rotational speed generally between 80 and 92 revolutions per minute, motor power settings between 90 and 110 kilowatts and water flow levels. Integrated sensors monitor oil pressure, motor rotation and material resistance during operation (Özfırat et al., 2017).

During the cutting phase, the flywheel drives the connecting rod mechanism to generate linear reciprocating motion of the blade frame. The trolley gradually rises while the blades progressively slice the block into slabs typically 2 to 3 centimeters thick. Daily production capacity may reach 200 to 300 square meters with surface roughness values approaching Ra ≤ 1.6 micrometers under optimal operating conditions (Özkan et al., 2015).

Cooling and sludge management constitute critical stages of the operation. High pressure water is continuously supplied to cool the diamond segments and reduce frictional heat. The resulting slurry is transported through discharge channels to cyclone separation systems where water is partially recycled, contributing to dust suppression and thermal stability (Varol, 2024). Once the desired slab thickness is reached, the system automatically stops based on thickness detection mechanisms. The cut slabs are removed using conveyors or overhead cranes. Fragile slabs may be reinforced with fiberglass prior to further processing and transferred to grinding and resin treatment units (Cunha Demartini et al., 2018). Previous FMEA applications in marble facilities

have identified vibration exposure and dust generation as critical operational risks, with hydrostatic support systems contributing to vibration mitigation during cutting operations (Dormishi et al., 2019).

2.3. Failure Mode and Effects Analysis Method

Failure Mode and Effects Analysis is a proactive and systematic risk assessment method based on identifying potential failures before they occur and implementing preventive measures rather than detecting and correcting failures after occurrence. The fundamental principle of the method involves determining possible failure modes within a process, evaluating their potential causes and effects and prioritizing corrective actions according to the magnitude of associated risks. Due to its structured yet practical approach, Failure Mode and Effects Analysis is widely recognized as one of the most effective risk assessment tools used in industrial systems (Özfırat, 2014).

The method was originally developed in the 1960s for applications in the aerospace industry, where system reliability and operational safety were critical. Over time, it has been extensively applied in automotive, chemical, manufacturing and mining industries due to its ease of implementation and limited requirement for complex theoretical modeling (Sharma and Srivastava, 2018).

The literature describes four primary forms of Failure Mode and Effects Analysis. Process FMEA examines risks that may arise during manufacturing and operational stages. System FMEA addresses the performance, reliability and safety of an integrated system as a whole. Design FMEA is conducted during the development phase to anticipate potential failures before production. Service FMEA, on the other hand, is applied to activities associated with service operations in order to enhance process effectiveness and reduce potential deficiencies. Within the scope of this study, Process FMEA was applied to evaluate operational risks associated with the gang saw machine. Each identified failure mode was assessed using three fundamental parameters: Occurrence, Severity and Detectability. Each parameter was scored using a numerical scale ranging from 1 to 10 (Stamatis, 2003).

Occurrence represents the probability of a failure taking place. The scoring criteria used in this study are presented in Table 1. Severity represents the impact of a failure on human safety, system integrity and operational continuity. The severity classification used in the study is presented in Table 2. Detectability represents the likelihood of identifying a potential failure before it leads to adverse consequences. The detectability scale used in the study is shown in Table 3 (Özkılıç, 2005; Wang et al., 2009; Kahraman and Demirer, 2010). Although Failure Mode and Effects Analysis is widely applied, the classical Risk Priority Number approach has several recognized methodological limitations. It treats Occurrence, Severity and Detectability as equally important and multiplies three ordinal scores, so different parameter combinations can yield identical Risk Priority Number values and the resulting scores are not uniformly distributed across the theoretical 1–1000 range. The method also depends on expert judgment, which introduces a degree of subjectivity. Recent studies have sought to overcome these shortcomings by integrating the method with fuzzy logic and multi criteria decision making techniques (Gao and Zhou, 2025; Toptancı et al., 2025). In the present study, three complementary measures were adopted to limit these drawbacks within the classical framework: a multidisciplinary expert panel was used instead of single evaluator scoring, each assigned score was cross checked against multiyear documentary evidence and Severity was additionally treated as an independent priority indicator so that high consequence failure modes were not overlooked even when their Risk Priority Number remained at a moderate level.

The application of Failure Mode and Effects Analysis in this study followed five sequential steps. First, hazard sources related to the gang saw machine were identified. Second, potential failure effects, underlying causes and existing control mechanisms were determined. Third, Occurrence, Severity and Detectability scores were assigned and corresponding Risk Priority Numbers were calculated using Equation 1. Fourth, failure modes were ranked according to their Risk Priority Numbers and corrective measures were defined. Finally, after the implementation of recommended measures, Risk Priority Numbers were recalculated to evaluate the effectiveness of the improvements (Stamatis, 2003). The Failure Mode and Effects Analysis conducted in this study was based on a structured expert evaluation process supported by historical operational data and field observations. In order to ensure technical accuracy and operational representativeness, a multidisciplinary expert team consisting of five members was formed within the facility. The expert panel included the production manager responsible for the cutting line, the chief maintenance engineer in charge of mechanical and hydraulic systems, the occupational health and safety specialist assigned to the facility, a senior gang saw operator with more than ten years of operational experience and an electrical maintenance technician responsible for control panels and sensor systems. The inclusion of both managerial and operational level personnel ensured that mechanical, electrical, operational and safety related perspectives were comprehensively reflected in the scoring process. Prior to scoring, a preliminary meeting was conducted to review the operational workflow of the gang saw machine and to define potential failure modes. Each identified failure mode was discussed collectively. Occurrence, Severity and Detectability scores were initially assigned individually by each expert using the 1 to 10 rating scales presented in Table 1, Table 2 and Table 3. The final score for each parameter was determined through consensus after group discussion. In cases where significant scoring differences emerged, historical records and maintenance logs were reviewed to support objective decision making. Determining each final score through group consensus rather than through a single evaluator reduced the influence of individual bias and limited random scoring variation, thereby improving the reproducibility of the

assessment. To confirm that the individual ratings assigned before group discussion were sufficiently consistent, the level of agreement among the five experts was quantified using Kendall's coefficient of concordance (W). The initial-round assessment yielded W = 0.78 ($P<0.05$), indicating an acceptable and statistically significant level of inter-rater reliability.

The corrective actions listed in Supplementary Table 5 were implemented at the facility during a dedicated improvement period of approximately four months following the initial assessment. All 26 corrective actions proposed by the expert panel were fully completed before the second evaluation was carried out. After implementation, a post-intervention observation period of approximately three months was allowed so that the effect of the measures could be assessed under routine production conditions rather than immediately after installation. The second scoring, which produced the RPN_2 values, was carried out by the same five-member expert panel that performed the initial evaluation, using the identical Occurrence, Severity and Detectability scales given in Tables 1, 2 and 3, so that the two rounds remained directly comparable. As in the first round, each RPN_2 parameter was rated individually and then finalized through group consensus, and inter-rater agreement was again verified using Kendall's coefficient of concordance ($W = 0.83$, $P<0.05$). This post-intervention verification procedure, together with the use of the same panel and the same rating scales in both rounds, was adopted to ensure that the reported risk reduction is methodologically reproducible rather than an artefact of differing evaluators or differing criteria. Multiple data sources were used to increase the reliability of the assessment. First, occupational accident records covering the previous five years were examined in order to identify recurring mechanical failures, operator related incidents and injury patterns associated with the gang saw machine. Second, near miss reports documented by the occupational safety unit were analyzed to capture incidents that did not result in injury but had high potential risk. Third, preventive and corrective maintenance records were reviewed to determine the frequency of mechanical breakdowns, hydraulic system failures, blade fractures and sensor malfunctions. These records provided quantitative insight into failure occurrence trends. Beyond the available records, field observations were carried out during both production shifts. Daily operating practices, operator interventions, vibration behavior of the machine, slurry discharge efficiency and block stabilization procedures were monitored directly within the production environment. This approach made it possible to detect operational deviations that were not clearly captured in maintenance logs or accident reports. Combining documented records with real time shop floor observations provided a more reliable basis for assigning FMEA scores. By integrating expert judgment with empirical operational evidence, the evaluation aimed to minimize subjectivity and provide a realistic representation of the risk profile associated with the gang saw machine.

The failure modes evaluated in this study were established through a structured screening process rather than an exhaustive listing. Candidate failure modes derived from the expert panel, five-year accident and near miss records, maintenance logs and field observations were retained when they satisfied at least one of the following criteria: a documented history of recurrence, a credible potential for severe injury or major equipment damage, or direct relevance to operator interaction during cutting. Modes that were redundant, negligible in consequence, or unrepresentative of routine gang saw operation were excluded. For exposure related failure modes such as excessive noise and vibration, Severity scores were additionally benchmarked against occupational exposure limit values defined in national and international regulations, namely daily noise exposure action values of 80 and 85 dB(A) and an exposure limit value of 87 dB(A) (Directive 2003/10/EC; Regulation on the Protection of Workers from Noise Related Risks, 2013), as well as daily hand–arm vibration action and limit values of 2.5 and 5 m/s^2 (Directive 2002/44/EC; Regulation on the Protection of Workers from Vibration Related Risks 2013). This procedure yielded the 26 representative failure modes analyzed in Section 3. Table 1, Table 2 and Table 3. The formulation is expressed in equation 1.

$$RPN = O \times S \times D \quad (1)$$

The resulting Risk Priority Number values were evaluated according to the classification presented in Table 4.

Table 1. Occurrence Rating Criteria (Özkılıç 2005; Wang et al. 2009; Kahraman and Demirer 2010)

Failure Probability Description	Approximate Probability	Rating
Very high, failure is almost inevitable	Greater than 1/2	10
	1/3	9
High, repeated failures	1/8	8
	1/20	7
Moderate, occasional failure	1/80	6
	1/400	5
Low, relatively few failures	1/2000	4
	1/15000	3
Very low, unlikely failure	1/150000	2
Extremely unlikely	Less than 1/150000	1

Table 2. Severity classification (Özkılıç, 2005; Wang et al., 2009; Kahraman and Demirer, 2010)

Effect Description	Severity Definition	Rating
Extremely hazardous without warning	Catastrophic effect without prior warning	10
Hazardous without warning	Severe damage and potential multiple fatalities	9
Very high	System destruction, severe injury, third degree burns, acute fatality	8
High	Complete equipment damage, poisoning, fatal injury	7
Moderate	Loss of limb or organ, serious injury, long term illness	6
Low	Fracture, minor permanent disability, second degree burns	5
Very low	Minor injury, cuts, bruises, short term discomfort	4
Minor	Slows system performance	3
Very minor	Causes operational confusion	2
None	No observable effect	1

Table 3. Detectability rating criteria (Özkılıç, 2005; Wang et al., 2009; Kahraman and Demirer, 2010)

Detection Level	Detectability Definition	Rating
Undetectable	Failure cause and subsequent failure cannot be detected	10
Very remote	Detection is highly unlikely	9
Remote	Detection is unlikely	8
Very low	Very low probability of detection	7
Low	Low probability of detection	6
Moderate	Moderate probability of detection	5
Moderately high	Above average probability of detection	4
High	High probability of detection	3
Very high	Very high probability of detection	2
Almost certain	Failure will almost certainly be detected	1

The Risk Priority Number is calculated by multiplying the Occurrence, Severity and Detectability scores obtained from

Table 4. Risk priority number evaluation criteria (Özkılıç, 2005; Wang et al., 2009; Kahraman and Demirer, 2010)

RPN Value	Required Action
RPN < 40	No action required
40 ≤ RPN ≤ 100	Action may be taken
RPN > 100	Immediate action required

3. Results

3.1. Identified Failure Modes

As a result of the structured Failure Mode and Effects Analysis conducted for the gang saw machine, a total of 26 potential failure modes were identified. These 26 modes were retained through the structured screening procedure described in Section 2.3, in which candidate failures were included on the basis of documented recurrence, severe injury or major damage potential and direct relevance to operator interaction, so as to present the most representative and critical risk items within a single comprehensive table. The identified failure modes were derived from expert assessments, historical maintenance records, occupational accident documentation, near miss reports and direct field observations. The selection process aimed to prioritize failure scenarios with direct implications for occupational safety, operational continuity and structural integrity of the cutting system.

The failure modes were categorized under mechanical, hydraulic, electrical and control, cooling and slurry management and operator related groups. This classification reflects the multi component nature of the gang saw system, which integrates dynamic mechanical motion, pressurized hydraulic stabilization, electrical control units and continuous cooling and discharge mechanisms. Mechanical failure modes included blade fracture, blade tension imbalance, connecting rod fastening loosening, flywheel bearing wear, linear guide clearance increase, block positioning misalignment and insufficient block fixation. These risks were considered critical because they directly influence dynamic stability during reciprocating motion and may lead to sudden load redistribution within the frame assembly. In particular, imbalance within the blade group may generate uneven stress distribution, increase vibration amplitude and reduce dimensional precision.

Hydraulic system related failures involved hose rupture, oil leakage, pressure instability and lifting asymmetry of the block trolley. Since hydraulic systems ensure vertical positioning and stabilization of marble blocks weighing several tons, any deviation in pressure control may result

in unstable cutting conditions. Electrical and control system failures included main motor overload, sensor calibration errors, PLC malfunction and electrical panel short circuit. Such failures may disrupt cutting parameters, delay emergency response, or generate secondary hazards due to unexpected system shutdowns. Cooling and process related risks consisted of cooling water flow reduction, pump malfunction, slurry discharge blockage and cyclone separation inefficiency. Inadequate cooling may increase blade temperature and accelerate wear, while slurry accumulation can create slip hazards and reduce visibility. Operator related risks such as intervention while protective guards are open, unsafe handling practices, excessive vibration exposure, excessive noise exposure, slippery floor conditions due to slurry spillage and insufficient illumination were also identified as significant contributors to the system risk profile. These hazards are closely linked to routine operational practices and work environment conditions.

The quantitative evaluation results are presented in Supplementary Table 5. Risk Priority Number values were calculated using the Occurrence, Severity and Detectability scores determined by the expert panel. Under current operating conditions, initial RPN values ranged from 162 to 294. The highest RPN value was recorded for blade tension imbalance (294), followed by blade fracture and operator intervention with guards open (288). Insufficient block fixation yielded an RPN of 280, while block overturning, cooling water flow reduction, excessive vibration exposure and slurry related floor slip hazards produced RPN values of 252.

Among the 26 identified failure modes, 20 produced initial RPN values above 200 under existing operating conditions. This concentration indicates that high risk items were not isolated but distributed across interconnected subsystems. Mechanical transmission elements and operator interaction points represented the most sensitive zones of the cutting line. When the initial values are examined by magnitude, they cluster into four discernible bands: a very high group of four modes scoring between 280 and 294 (blade tension imbalance, blade fracture, operator intervention with guards open and insufficient block fixation); a high group of eight modes between 224 and 252, dominated by environmental–ergonomic and structural risks; a moderate to high group of eight modes between 210 and 216, mainly hydraulic and electrical in nature; and a lower group of six modes below 200. All 26 modes initially exceeded the RPN > 100 threshold defined in Table 4, meaning that every evaluated failure mode required immediate corrective action under existing conditions. After the implementation of the proposed corrective actions, recalculated RPN values showed a consistent downward shift across all evaluated failure modes. All 26 failure modes were reduced to levels below 100 and the mean Risk Priority Number decreased from 226.2 to 50.3, corresponding to an overall reduction of approximately 77.7 %. Individual reductions ranged from about 67 % to 89 %. Following intervention, 22 modes fell into the 40–100 band, for which action may still be considered, while 4 modes dropped below 40, indicating that no further action was required. The reduction pattern reflects decreased Occurrence and improved Detectability scores, while Severity values remained largely unchanged due to the inherent consequence level of potential failures. These findings underline the importance of structured maintenance routines, parameter control procedures and controlled operator intervention in reducing operational risk within gang saw operations.

3.2. FMEA Results

The quantitative findings of the FMEA application are summarized in Supplementary Table 5. A total of 26 failure modes were evaluated under existing operating conditions and after corrective measures. Initial Risk Priority Number scores (RPN_1) ranged from 162 to 294, reflecting different levels of exposure across mechanical, hydraulic, electrical and operator related categories. Blade tension imbalance produced the highest score (294), followed by blade fracture and operator intervention with guards open (288). Insufficient block fixation reached 280, while block overturning, cooling water flow reduction, vibration exposure, noise exposure and slurry induced slip hazards each resulted in 252.

When the distribution of RPN_1 values is examined numerically, **20** of the 26 failure modes produced scores above 200 under current operating conditions. This indicates that a substantial portion of the evaluated risks required immediate corrective action according to the classification criteria presented in Table 4. In fact, all 26 modes initially exceeded the RPN > 100 threshold, so every evaluated failure required action, while the 20 modes above 200 represented the most urgent subset. The concentration of high RPN_1 values was particularly evident within the mechanical transmission system, including blade assembly components, fastening elements and structural support mechanisms. Failures related to dynamic imbalance and inadequate fixation demonstrated higher Severity and Detectability scores, which significantly increased total RPN values even when Occurrence levels were moderate.

Hydraulic failures such as hose rupture (210) and oil leakage (216), along with electrical issues including main motor overload (210) and sensor calibration error (210), also represented considerable sources of operational exposure within the system. Although these failure modes did not reach the highest RPN_1 range, their technical nature and potential for secondary consequences justified structured preventive measures. Emergency stop system failure showed the lowest RPN_1 value (162), primarily due to lower Occurrence scores and existing inspection routines.

Following the implementation of corrective actions defined in Supplementary Table 5, recalculated RPN_2 scores declined consistently across all evaluated failure modes. The highest residual score was recorded as 72 for blade fracture**, insufficient block fixation and excessive

noise exposure. Several previously critical risks, including blade tension imbalance, block overturning, hydraulic hose rupture and PLC malfunction, were reduced to RPN_2 values between 42 and 63. The majority of failure modes shifted into the 30–60 range after intervention. Overall, the mean RPN_1 of 226.2 fell to a mean RPN_2 of 50.3, an average reduction of approximately 77.7 %, with individual reductions ranging from about 67 % to 89 %. The largest absolute decreases occurred among blade mechanics and operator interaction modes; for example, operator intervention with guards open fell from 288 to 54 (a reduction of 81 %) and blade tension imbalance from 294 to 63 (a reduction of 79 %). After intervention, no failure mode remained above the RPN > 100 action threshold and four modes dropped below 40 into the no action required band defined in Table 4.

The numerical comparison between RPN_1 and RPN_2 values shows a clear decline in risk levels across the cutting system. The most pronounced reductions were observed in failure modes associated with blade mechanics and operator interaction. Severity scores remained unchanged, as they represent the inherent consequences of a failure; however, Occurrence and Detectability scores decreased following the introduction of structured procedures, monitoring devices and preventive maintenance routines. This shift reflects improved control over failure probability and earlier identification of deviations during operation. The resulting RPN_2 distribution moved the majority of failure modes into moderate risk ranges, supporting safer and more controlled operating conditions within the gang saw line.

4. Discussion

The FMEA results presented in Supplementary Table 5 indicate that risk accumulation within the gang saw system is predominantly linked to blade mechanics, block stability and unsafe operator behavior. Among all evaluated failure modes, blade tension imbalance produced the highest initial RPN value (RPN_1 = 294). This outcome reflects the sensitivity of the reciprocating cutting mechanism to minor deviations in torque distribution. Uneven blade tension increases stress concentration along the frame and directly contributes to accelerated wear and sudden fracture. Similar mechanical instability issues have been reported in marble cutting facilities where improper blade calibration significantly increased accident potential (Eleren and Ersoy, 2011).

Blade fracture (RPN_1 = 288) and operator intervention while protective guards were open (RPN_1 = 288) emerged as the next most critical risks. The close similarity of these values suggests a clear interaction between mechanical stress and unsafe operational behavior. While blade fatigue develops gradually due to repetitive loading, unauthorized intervention during active cutting exposes operators to sudden and uncontrolled mechanical forces. Previous studies in heavy stone processing environments report that time pressure and routine familiarity may lead workers to bypass protective systems, increasing accident probability (Haghighi et al., 2019). In the analyzed facility, the integration of interlock systems together with stricter operational supervision noticeably reduced residual RPN values, indicating that technical modifications combined with procedural discipline can effectively limit such risks.

Block fixation related failures also ranked among the highest risk categories. Insufficient block fixation (RPN_1 = 280) and block overturning (RPN_1 = 252) are directly associated with the mass and structural instability of marble blocks. Given the kinetic energy involved, even minor fixation errors may produce severe consequences. Comparable findings have been documented in heavy lifting and material handling systems, where sensor-based stability monitoring reduced overturning events (Yoon et al., 2021). In this facility, the addition of hydraulic pressure sensors and procedural verification steps significantly reduced these risks.

Environmental and ergonomic risks, including excessive vibration exposure, noise exposure and slurry induced slip hazards (each RPN_1 = 252), represent cumulative rather than instantaneous threats. Although these risks may not result in catastrophic accidents, prolonged exposure can lead to long term occupational health problems such as hearing impairment and musculoskeletal disorders. The introduction of vibration control monitoring, reinforced personal protective equipment enforcement and improved housekeeping practices effectively reduced these risk levels to moderate ranges.

When these findings are compared with previous FMEA applications in the marble and natural stone sector, both agreements and distinctions emerge. Plant wide studies have consistently identified cutting and lifting operations as the dominant risk zones (Ersoy et al., 2017; Önder et al., 2022), which is consistent with the concentration of high RPN_1 values observed here around blade mechanics and block handling. However, because those studies aggregate hazards across the whole facility, they do not isolate machine internal failure mechanisms such as blade tension imbalance, connecting rod loosening, or trolley lifting asymmetry, which were among the most critical modes in the present analysis. The machine level resolution adopted in this study therefore reveals risk drivers that remain largely invisible at the plant scale. Methodologically, more recent fuzzy and MCDM based FMEA studies in comparable settings (Gul and Ak, 2021; Gao and Zhou, 2025) have shown that incorporating expert uncertainty and unequal criterion weights can refine the ranking of failure modes; while the present study relies on the classical RPN with consensus scoring, the direction of its priority ranking is broadly consistent with these advanced approaches, supporting the robustness of the identified critical modes.

High RPN_1 values were mainly concentrated in mechanical transmission components and operator interaction zones. The consistent reduction observed in RPN_2 values across all failure modes confirms that

structured corrective measures, particularly those grounded in engineering modifications and systematic maintenance planning, can significantly enhance operational safety in marble processing facilities. Beyond the specific facility examined, the results carry broader implications for heavy stone cutting operations and, more generally, for reciprocating and multi blade cutting systems that share the same combination of dynamic mechanical motion, hydraulic stabilization of heavy loads and close operator interaction. The corrective logic that proved most effective here—shifting from operator dependent visual control toward instrumented monitoring, interlocks and standardized procedures—is transferable to circular and wire saw lines, block handling stations and similar equipment in other natural stone plants. The machine level FMEA framework can thus serve as a repeatable template that facility managers may apply unit by unit to build a plant wide risk profile from the bottom up, prioritizing engineering resources where residual severity remains high even after probability and detectability have been improved.

5. Conclusion

This study presented a structured Failure Mode and Effects Analysis conducted on a gang saw machine operating in a marble processing facility located in the Aegean Region of Türkiye. A total of 26 potential failure modes were systematically identified and evaluated under current operating conditions using Occurrence, Severity and Detectability parameters. The initial Risk Priority Number values ranged between 162 and 294, indicating a significant concentration of risk within specific mechanical and operator related domains.

Blade tension imbalance, blade fracture, unsafe operator intervention and insufficient block fixation represented the most critical risk categories identified in the analysis. These failure modes are closely related to the dynamic behavior of the reciprocating cutting mechanism and the substantial mass of marble blocks processed during operation. In addition, environmental and ergonomic factors such as vibration exposure, noise exposure and slurry induced slip conditions contributed noticeably to workplace risk. Although these factors may not cause immediate catastrophic events, repeated exposure may lead to cumulative occupational health effects.

Following the implementation of engineering controls, structured maintenance procedures and reinforced operational protocols, recalculated RPN values demonstrated a substantial reduction across all failure modes. Most previously critical risks decreased to moderate or acceptable levels, confirming the effectiveness of systematic risk prioritization and corrective action planning. In quantitative terms, the mean Risk Priority Number fell from 226.2 to 50.3, an overall reduction of approximately 77.7 % and no failure mode remained above the immediate action threshold after intervention.

The findings indicate that applying FMEA at the machine level provides a clear and measurable framework for identifying critical vulnerabilities in heavy stone cutting operations. The approach enables facility managers to prioritize resources, strengthen preventive maintenance planning and improve occupational safety performance. From a practical standpoint, the study offers facility managers a concrete and low-cost decision-making tool: by ranking failure modes and recalculating risk after intervention, limited engineering and maintenance budgets can be directed first toward the modes with the highest residual severity and the measurable before and after reduction provides objective evidence of safety improvement that can support audits, investment justification and regulatory compliance. The most effective measures identified here—instrumented monitoring, interlocks and standardized written procedures replacing operator dependent visual control—are directly implementable in comparable stone cutting facilities.

Nevertheless, this study has certain limitations. It relies on the classical Risk Priority Number, which assumes equal weighting of the three parameters and is based on consensus expert scoring at a single facility, so the absolute values may not be directly generalizable. Future research may address these limitations by extending the approach to other production units within marble processing facilities and by integrating FMEA with fuzzy logic and multi criteria decision making methods such as AHP, TOPSIS, or DEMATEL to better handle uncertainty and unequal criterion weights (Gul and Ak, 2021; Toptancı et al., 2025). The accumulation of maintenance, sensor and accident data over time could further enable data driven and machine learning based prediction of failure occurrence, moving machine level risk assessment from a periodic expert exercise toward continuous, condition-based monitoring.

Author Contributions

The percentages of the author' contributions are presented below. The author reviewed and approved the final version of the manuscript.

	A.K.E.
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The author declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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