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Evaluating and Implementing Improved Safety Systems in Vertical Milling Machines

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Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: 

Date: 13/05/25

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Abstract

This project investigates and implements improved safety measures for vertical milling machines within Renishaw's Custom Workshop, addressing significant entanglement hazards posed by exposed rotating tooling. Existing guarding solutions were evaluated through a detailed literature review, historical accident data and current health and safety regulations. Modern safety technologies, including conductive sensors, pressure mats and interlocked guards were assessed using Failure Modes and Effects Analysis (FMEA) and Multi-Criteria Decision Analysis (MCDA) to determine the most suitable solution.

An adjustable interlocked guard system was selected based on its strong performance in risk reduction, ease of integration and operational efficiency. The system underwent mechanical testing in accordance with ISO 14120, operator efficiency trials and user feedback collection. Results showed a twenty per cent improvement in workflow efficiency and an estimated annual labour cost saving exceeding sixteen thousand pounds. Survey responses confirmed enhanced operator confidence, usability and safety perception.

The implemented solution achieved a first-year return on investment of approximately three hundred ninety per cent while significantly reducing the risk of injury. The project presents a structured and replicable methodology for enhancing machine safety and offers practical insight into integrating modern safety systems within manual machining environments.

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1 Introduction

1.1 Project background

This project is being conducted in the Custom Workshop, a newly developed machining facility located at Renishaw's Miskin site. The Custom Workshop was established in 2022 to provide shorter lead times for bespoke stylus designs previously outsourced. Additionally, the facility aims to improve lead times for ad hoc and modified tooling to support the site's increasing manufacturing scale. The workshop has automatic and manual machining equipment for drilling, milling, turning, and grinding operations. Risk assessments were conducted on all equipment in the facility, highlighting concerns regarding entanglement risks on the vertical milling machine.

Currently, the facility houses three employees: the author, whom is a development machinist, another development machinist and a mechanical engineering apprentice. The author's role within this facility is to liaise and carry out job requests from internal customers.

1.2 Define problem

Vertical milling machines present significant safety hazards, primarily due to the rotating spindle that houses tooling such as drills and end mills. The tooling is located in the spindle and rotated at high speeds to remove material from the workpiece, which is mounted to the table, as illustrated in Figure 1. This rotating tooling can cause injuries such as cuts and lacerations and amputations in more serious incidents. Despite these machines being utilised in engineering workshops worldwide for many years, the flexibility regarding setup and operations means preventing danger is difficult without hindering productivity. Existing safety measures, such as guards, are designed in order to avoid access to these dangerous parts. However, rotating cutters may still be accessible due to design limitations, maintenance activities, improper use, or wear and tear. These factors can leave parts of the cutter exposed, especially during setup or maintenance when guards might be removed. Additionally, flying debris, noise and manual handling of workpieces further contribute to the risks associated with manual milling machines. Regular inspection, proper training and adherence to safety protocols are essential to mitigate these hazards.

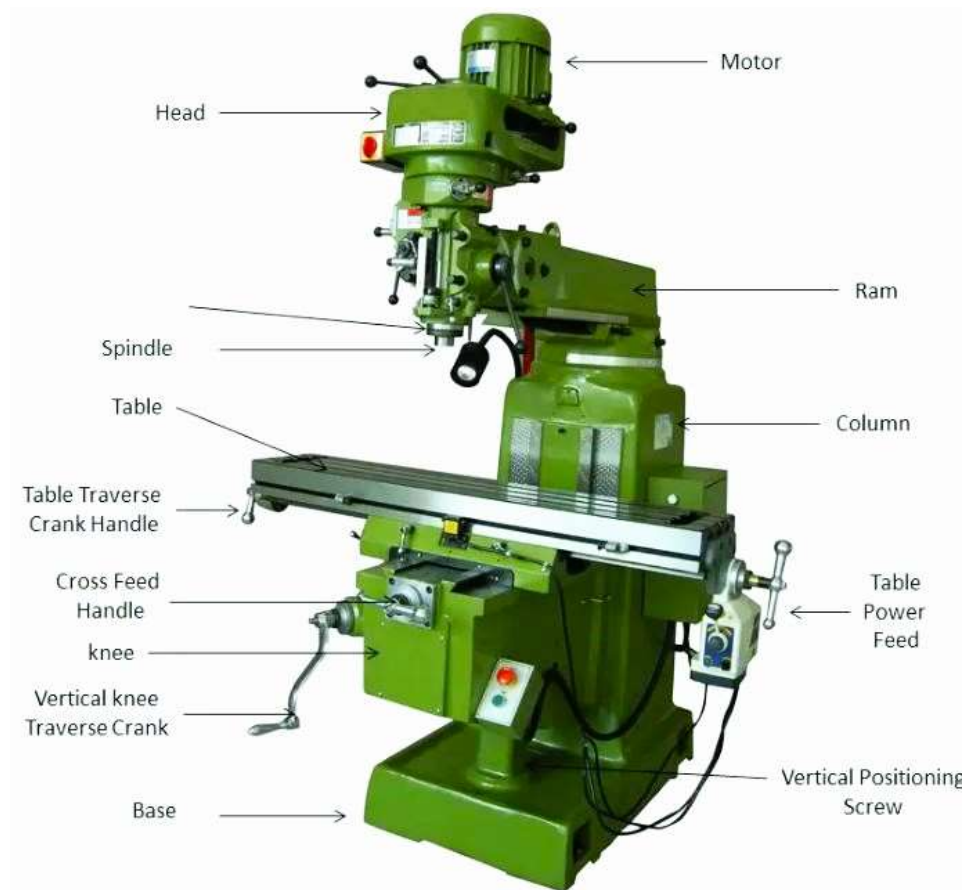


Figure 1 - Vertical Milling Machine parts (CNCYangsen, 2023)

1.3 Project Aim & Objectives

1.3.1 Aim

To evaluate and implement the most appropriate safety system for the vertical milling machine in Renishaw's Custom Workshop.

1.3.2 Objectives

1. Identify current safety risks.
2. Evaluate existing and potential safety systems.
3. Select and integrate the best safety system within the budget.
4. Measure the effectiveness of the selected safety system.
5. Assess cost-benefit analysis.
6. Analyse data and provide recommendations.

1.4 Report structure

This report is structured comprehensively to facilitate a clear understanding of the project. The Introduction section sets the stage by defining the problem, providing an overview of relevant manufacturing aspects and outlining the aims and objectives of the project. The Literature Review offers context and background information by examining existing literature, focusing on the evolution of safety standards, health and safety regulations and past accident rates in manual milling operations. The current guarding section evaluates different guarding solutions, including fixed adjustable, and interlocked guards, emphasising their benefits and applications. The modern safety system section delves into advanced safety technologies such as passive infrared sensors, light curtains and other modern safety systems, highlighting their significance in contemporary manufacturing.

The Relevant Enterprises section discusses companies like Sawstop and Bladestop that have pioneered advanced safety measures. Decision-Making Tools are explored through the application of Failure Modes and Effects Analysis (FMEA) and decision matrices, which are discussed to help identify the most suitable guarding option. The design and development section details the project's methods, initial design concepts and the application of decision-making tools. Procurement aspects, including requirements, budget considerations, vendor selection, and equipment procurement are addressed in the purchasing section. The installation plan outlines the detailed installation process for the new equipment. The results and discussion section presents the outcomes of the project and their implications. The Cost-Benefit analysis evaluates the financial aspects of the project, while the conclusion summarises key findings and outcomes. Finally, the recommendations for future work suggest areas for further research or improvement, ensuring a comprehensive project exploration.

1.4.1 Gantt chart

This project used a Gantt chart to create a clear understanding of the project's progress. A Gantt chart is a crucial project management tool visually representing project timelines and dependencies. Its horizontal bar format provides an overview, aiding resource allocation and deadline management by highlighting task dependencies and potential delays. It also promotes accountability by clearly assigning responsibilities. According to the Project Management Institute, visual tools like Gantt charts significantly enhance project management efficiency and communication (Project Management Institute, 2021). This is

supported by academic studies, which show improved project outcomes through better planning and coordination (Dufková, 2023).

The initial Gantt chart, Figure 2, provides a structured timeline that aligns with the report structure. Starting with the proposal submission and supervisor meetings, the project progresses through critical milestones such as researching current guarding systems and sensor technologies, understanding process flows and defining project aims and objectives. These early stages set the foundation for the literature review which examines the evolution of safety standards, health and safety regulations, and historical accident rates. Subsequent tasks, including the design and purchasing of components, integration with the machine, testing and safety analysis, correspond to the design and development and installation plan sections of the report. The results and discussion, cost-benefit analysis and conclusion sections are supported by the project's later stages, ensuring that findings are evaluated and presented.

ENHANCING SAFETY IN MILLING MACHINES THROUGH THE INTEGRATION OF CONDUCTIVE FLESH DETECTION TECHNOLOGY

Emyr Hunnam

Renishaw PLC

Project Start Date: 03/10/2024

Scrolling Increment: 1

Legend:

On track Low risk Med risk High risk Not Started

Milestone description	Category	Assigned to	Progress	Start	Days
Proposal Submission	Milestone	EH	100%	04/10/2024	1
Supervisor meeting	On Track	EH, KL & KR	100%	01/11/2024	1
Contents page	Low Risk	EH	100%	05/11/2024	3
Research current guarding systems and sensor technologies	High Risk	EH	100%	08/11/2024	7
Process flow, understanding the process	Med Risk	EH	100%	15/11/2024	7
Project Aims & Objectives	High Risk	EH	100%	22/11/2024	6
Literature Review	High Risk	EH	1000%	28/11/2024	10
Complete Literature Review	Goal	EH	100%	04/12/2024	1
Prepare Presentation	Med Risk	EH	100%	05/12/2024	5
Interim Viva	Milestone	EH	0%	11/12/2024	1
Respond to Viva Feedback	Low Risk	EH	0%	13/12/2024	28
Design & Purchasing of required components	High Risk	EH	0%	10/01/2025	28
Integration with machine	High Risk	EH	0%	07/02/2025	35
Testing and safety analysis	High Risk	EH	0%	14/03/2025	21
Results and discussion	Med Risk	EH	0%	04/04/2025	14
Cost-Benefit analysis	Med Risk	EH	0%	18/04/2025	7
Write a project conclusion	Med Risk	EH	0%	25/04/2025	7
Referneces and Appendices	Med Risk	EH	0%	02/05/2025	7
Final checks	Low Risk	EH	0%	09/05/2025	7
Report Submission	Milestone	EH	0%	19/05/2025	1
Create Final Presentation	High Risk	EH	0%	30/05/2025	14
Create Poster	High Risk	EH	0%	13/06/2025	14
Final Oral Exam	Milestone	EH	0%	27/06/2025	1

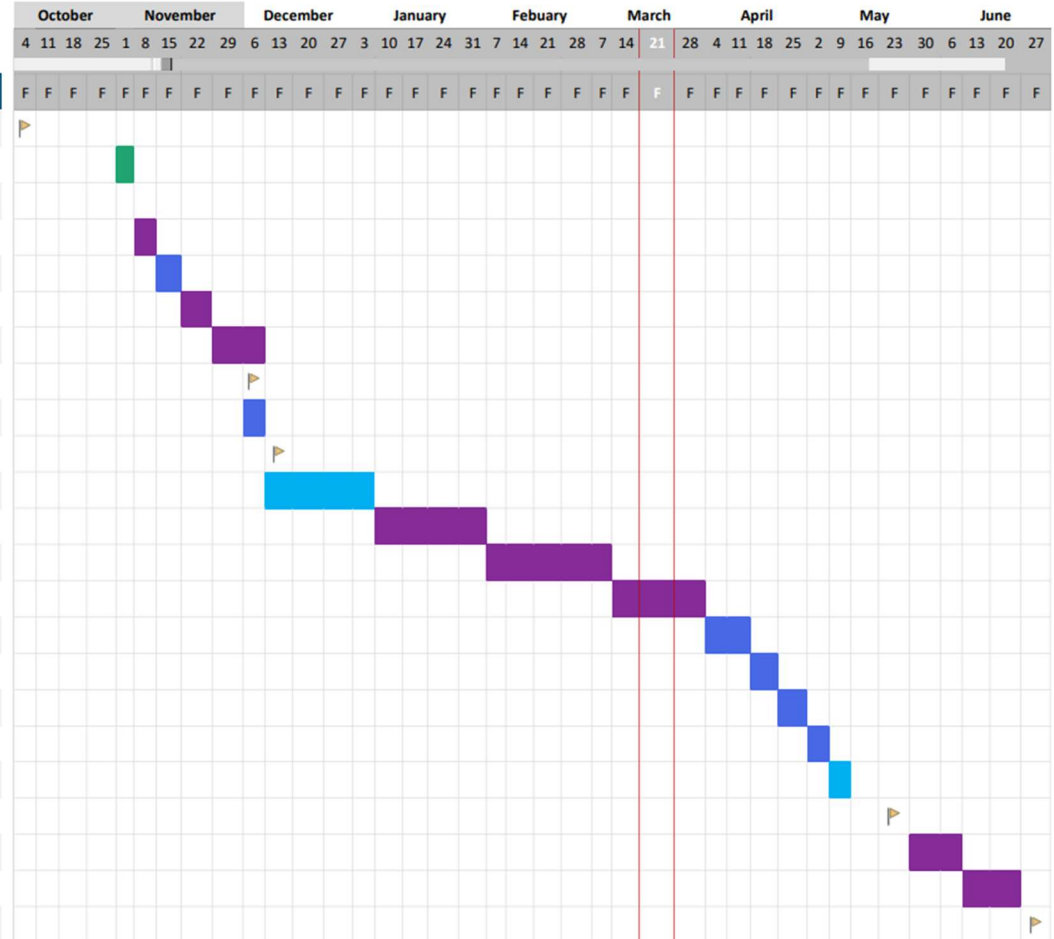


Figure 2 - Initial Gantt chart

2 Literature Review

This literature review examines research on entanglement hazards associated with vertical milling machines and also explores strategies for enhancing operator safety. Manual vertical milling machines offer significant advantages in flexibility and cost-effectiveness for small-scale production and prototyping. However, they also present significant risks, particularly concerning entanglement with rotating parts. The inherent nature of manual milling, involving close interaction between the operator and moving machine components, creates a high potential for accidents. These accidents range from minor injuries like lacerations to severe incidents involving amputations or fatalities. The consequences extend beyond immediate physical harm, including lost productivity, increased healthcare costs, and potential legal ramifications for employers. This review analyses existing literature on accident causation, preventative measures, machine design improvements, and operator training protocols to identify effective strategies for minimising entanglement incidents. The goal is to synthesise current knowledge, highlight areas needing further research, and contribute to the development of safer practices within the manual milling industry. The review focuses on the interaction between human factors, machine design, environmental conditions, and the effectiveness of various safety interventions.

2.1 Historical context of vertical milling machine safety

2.1.1 Introduction

This section is crucial for understanding the evolution of safety standards in manual milling machines, highlighting advancements in technology and regulations like PUWER 1998 and the Machinery Directive. These standards emphasise hazard elimination and risk management, essential for improving milling machine safety. Historical accident data and financial implications underscore the need for robust safety measures. By exploring these aspects, the project can identify gaps in current practices and advocate for advanced sensor technologies and emergency stop systems, ultimately enhancing safety in milling operations.

2.1.2 Evolution of manual milling machine safety standards

The evolution of manual milling machine safety standards reflects significant advancements in technology and a growing emphasis on workplace safety. Initially, safety measures were

rudimentary, focusing primarily on basic mechanical safeguards and operator training. However, as industrial processes became more complex, the need for comprehensive safety standards became evident. The introduction of regulations such as the Provision and Use of Work Equipment Regulations 1998 (PUWER) and the Machinery Directive (Directive 2006/42/EC) marked a shift towards safety approaches that prioritise hazard elimination, risk assessment, and proactive management. These regulations mandate that machinery be designed and maintained to minimise risks, incorporating advanced safety features and regular inspections. The Health and Safety at Work Act 1974 further underpins these efforts by imposing a fundamental duty of care on employers to implement robust safety protocols. However, Geller argues that behavioural safety and proper operator training are more effective than engineering controls in preventing workplace accidents (Geller, E, 2011).

2.1.3 Occupational health and safety regulations in manufacturing

Modern engineering workshops navigate a complex landscape of safety regulations with the Health and Safety Executive's HSG129 providing a comprehensive framework for managing machinery-related risks (Health and Safety Executive, 1999). Central to this approach are key regulatory requirements, including the Provision and Use of Work Equipment Regulations (PUWER) 1998 and the Machinery Directive, which mandate systematic safety strategies that prioritise hazard elimination and proactive risk management.

The Health and Safety at Work Act 1974 lays the groundwork for ensuring employers take their duty of care seriously, especially as human-machine interactions become more complex. With technology advancing, safety regulations have also evolved, adopting more adaptive and sophisticated risk management strategies. At present, it's not just about preventing accidents but also about using advanced monitoring and predictive safety technologies to foresee and address potential workplace hazards (Health and Safety Executive, 1974).

In the context of enhancing manual milling machine safety through modern technology integration, health and safety regulations provide a critical theoretical and practical foundation. The Health and Safety Executive's HSG129 and regulations like PUWER 1998 emphasise risk management approaches that align directly with innovative technological interventions.

2.1.4 Historical accident rates in manual milling operations

The Health and Safety Executive (HSE) provides critical insights into workplace safety through comprehensive statistical analysis, revealing significant challenges in industrial risk management, particularly within high-risk sectors such as manufacturing and machining (Health and Safety Executive, 2024a).

Recent occupational health and safety data demonstrates the persistent risks associated with machinery interactions. As Figure 3 shows the number of non-fatal injuries to manufacturing employees has drastically reduced over the last few decades. However, for the period 2023/24, there were over 60,000 reported non-fatal injuries to manufacturing employees in the UK, with 1,675 incidents (76.1%) resulting in absences exceeding seven days (Health and Safety Executive, 2024a). This statistic not only quantifies the immediate physical impact but also suggests substantial economic and operational disruptions for industries relying on manual machinery. It is important to note that the dip from 1981 to 1985 is attributed to a change in the source of data.

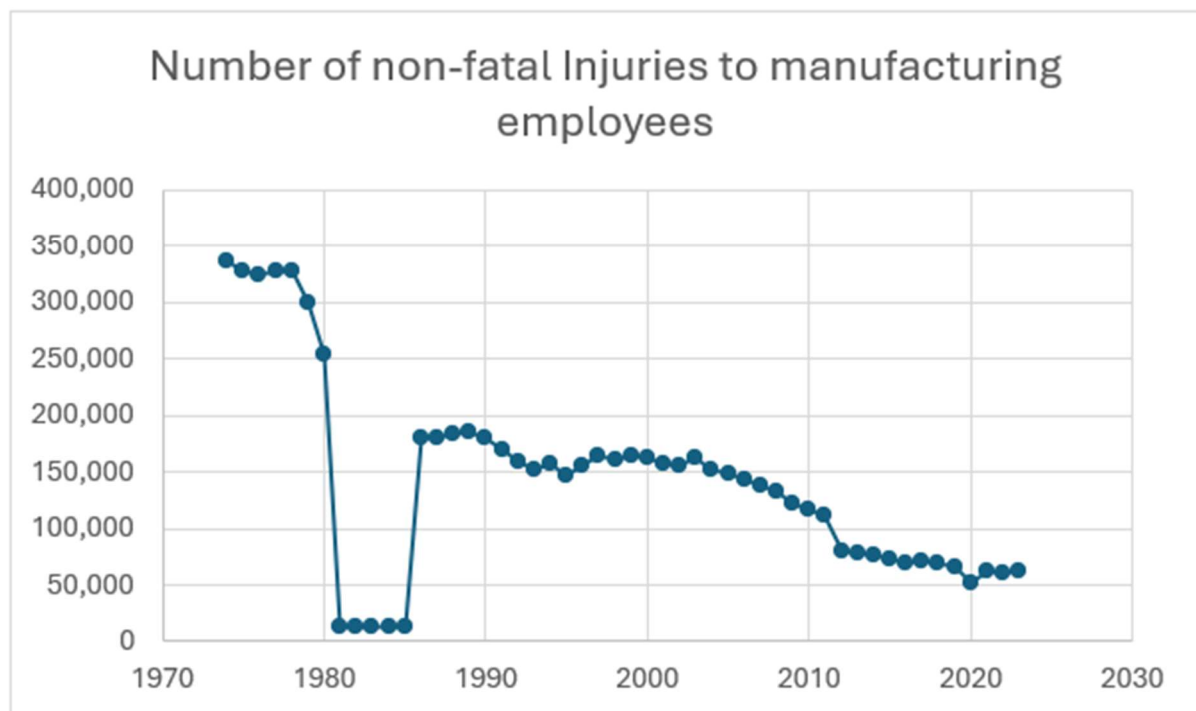


Figure 3 - Number of non-fatal injuries to manufacturing employees from (HSE, 2025)

Industry-specific analyses reveal particularly acute risks within machining environments. Out of 88 reported non-fatal injuries in the UK machining sector during 2023/24, 64 cases (72.7%) involved extended workplace absences, indicating the severe functional implications of machinery-related accidents (Health and Safety Executive, 2024b).

This extends beyond non-fatal incidents. Between 2021 and 2024, four employee fatalities were directly attributed to contact with moving machinery in manufacturing sectors. The broader context becomes even more alarming with 13 employee deaths recorded in the 2023/24 period alone (Health and Safety Executive, 2024d). When comparing Figure 3 and Figure 4, it becomes clear that whilst fatal injuries in manufacturing have dropped considerably, the number of non-fatal injuries has not followed suit, outlining the need for improved safety.

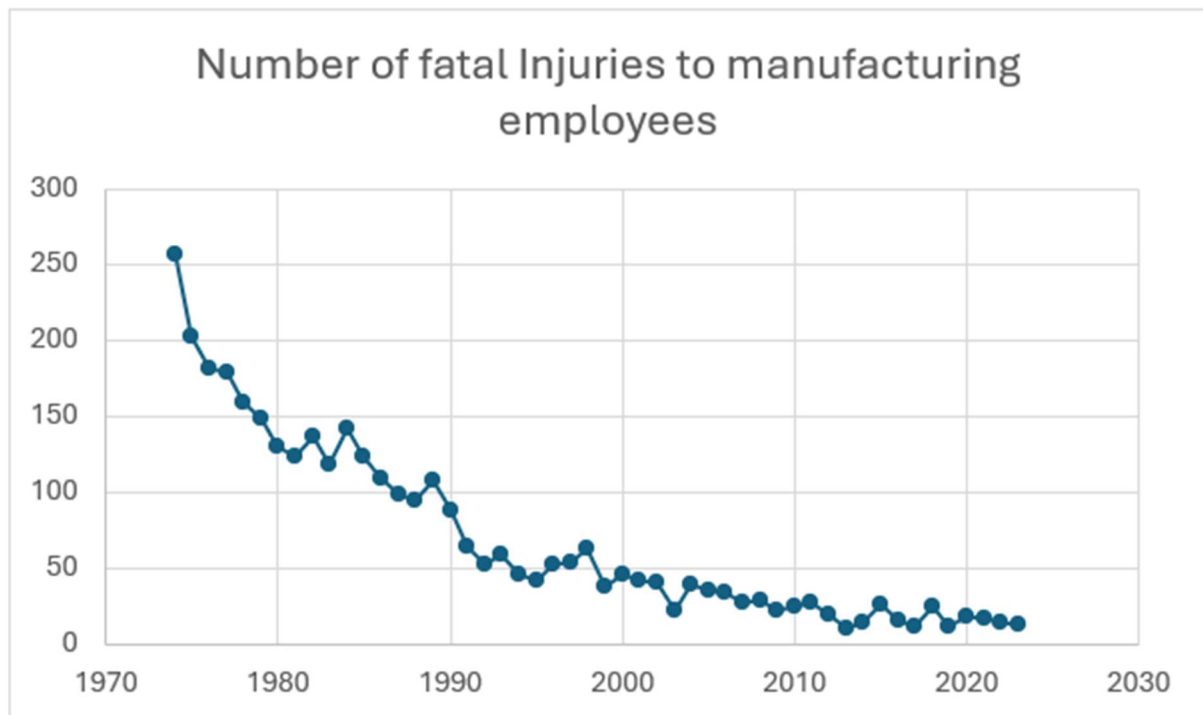


Figure 4 - Number of fatal injuries to manufacturing employees (HSE, 2025)

Injury severity statistics further emphasise the urgent requirement for comprehensive safety strategies. In 2023/24, 508 workplace-related amputations and 5,940 lacerations and open wounds were documented, highlighting the potential for catastrophic and life-altering injuries (Health and Safety Executive, 2024c).

2.1.5 Financial implications

Ensuring employee safety in manufacturing environments is crucial due to the significant financial implications of workplace injuries. Recent cases highlight severe penalties for inadequate safety measures, such as a £25,000 fine for an engineering firm after a hand injury on a lathe (Reals, 2024). Figure 5 shows that the average HSE fine that companies

receive after machining workplace injuries is almost £250,000. These fines, along with legal fees, compensation costs, increased insurance premiums, productivity losses, and reputation damage emphasise the financial risks associated with workplace injuries.

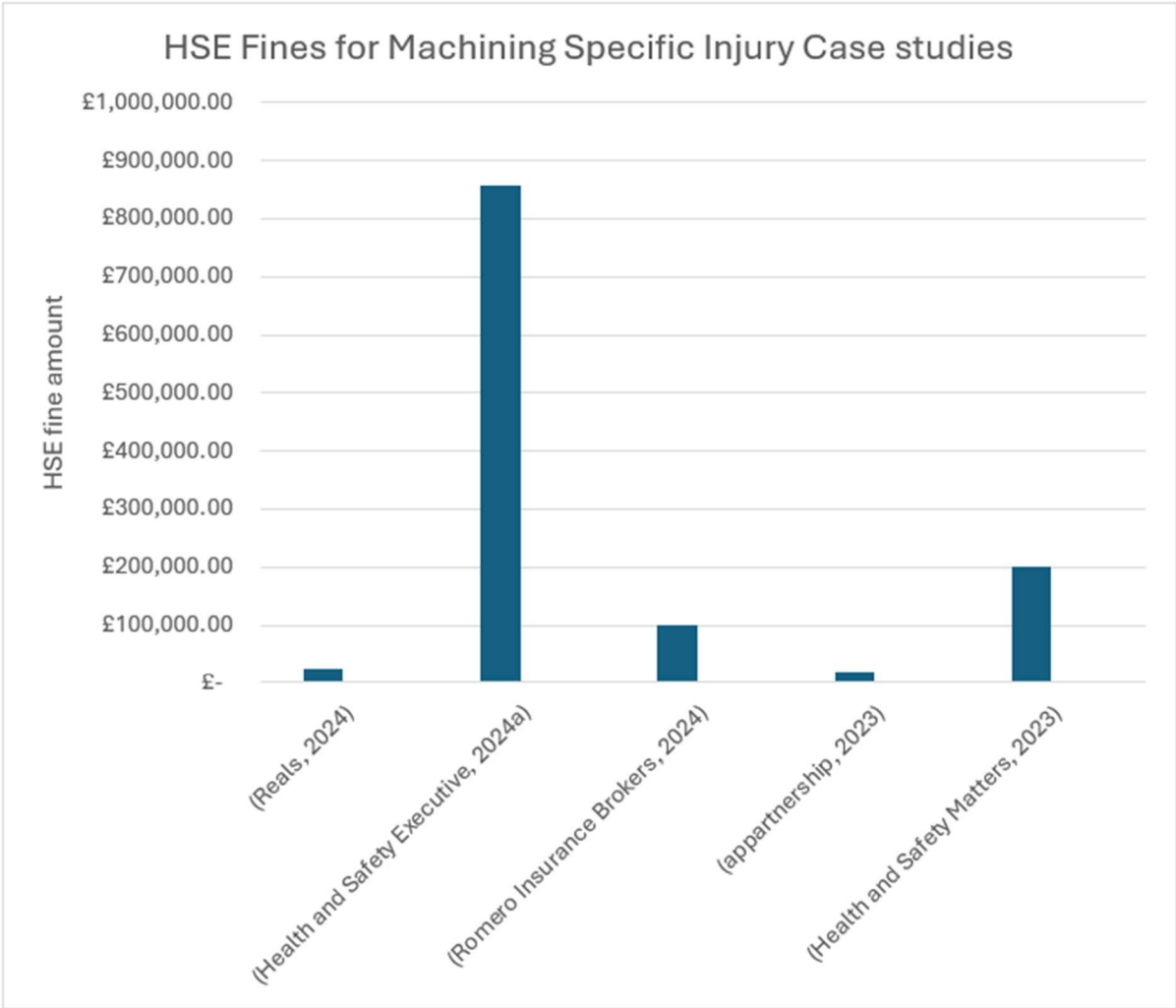


Figure 5 - HSE fines for Machining Specific Injury cases.

For Renishaw, investing in robust safety measures like advanced guarding systems and sensor technology is essential to mitigate these risks. By prioritising safety, Renishaw can protect their employees and avoid substantial financial losses, ensuring a safer working environment and maintaining their industry reputation. As Renishaw stated in their 2021 corporate responsibility report, “We also need to hear how our people are feeling in terms of wellbeing, and to ensure that we are providing a safe place to work.”, (Renishaw plc, 2021). The financial benefits of such investments far outweigh the costs, making it a prudent strategy for long-term operational stability and success.

2.1.6 Summary

These statistics highlight the complicated nature of industrial safety, showing that current protective measures are not enough. The data makes a strong case for researching advanced sensor technologies and integrated emergency stop systems as ways to improve safety.

2.2 Current guarding options for vertical milling machines

Manual vertical milling machines are critical for development work at Renishaw's Miskin site, accounting for approximately 20% of all development milling machines, including CNC models. However, they pose significant safety risks if not adequately guarded. Other manual milling machines, such as horizontal milling machines, also require guarding; however, this project will not focus on these, as they are much less common, and none are located at Miskin. Guarding systems are designed to protect operators from hazardous moving parts while maintaining operational efficiency. This section discusses current vertical milling machine guarding options, considering their alignment with regulatory requirements, practical implementation and overall effectiveness.

2.2.1 Fixed guards

Fixed guards are stationary barriers that enclose hazardous areas of a machine, requiring tools for adjustments, see Figure 6. According to the HSE, these guards are the preferred method for protecting operators from moving parts, as they provide reliable and continuous protection (HSE, 2023). Fixed guards are cost-effective and require minimal maintenance, making them suitable for repetitive tasks in controlled environments.



Figure 6 - Fixed Milling Machine Guard (Silvaflame-Cleervue, 2025)

Although they possess many benefits, fixed guards lack flexibility, potentially obstructing visibility and complicating operations that involve diverse workpiece sizes or machining setups. The setup shown in Figure 7 is an example of this, where the head is tilted to machine horizontally there is no room for a fixed guard to be mounted. Despite these drawbacks, their simplicity and compliance with regulatory standards make them a widely adopted solution in many workshops.



Figure 7 - Complex milling machine setup in Custom Workshop

2.2.2 Sliding interlocked door guards

Sliding interlocked door guards prevent the machine from operating unless the sliding doors are fully closed, see Figure 8. These systems are common in CNC environments but are being adapted for manual machines to enhance safety. The integration of mechanical and electrical interlocking mechanisms ensures an elevated level of protection by physically or electronically linking machine operation to guard status. While sliding interlocked door guards significantly reduce the risk of operator exposure, they are more complex and costly than fixed guards. Additionally, their mechanical or electrical components may be prone to failure, potentially causing machine downtime. It is noteworthy that interlocks are not mandated by HSE guidelines for manual milling machines, which may limit their adoption in certain settings.



Figure 8 - Interlocked Milling Machine Guard (PUWER Machinery Guarding, 2025b)

2.2.3 Adjustable interlocked guards

Adjustable guards address the limitations of fixed systems by allowing operators to reposition or resize the guard based on the requirements of a specific machining operation, see Figure 9. This adaptability makes them particularly useful in environments where workpiece dimensions and machining configurations vary. However, the reliance on manual adjustments introduces the risk of improper use or complete removal, potentially compromising safety. While adjustable guards offer a balance between flexibility and protection, their effectiveness is highly dependent on operator training and adherence to safety protocols.



Figure 9 - Adjustable interlocked guard (PUWER Machinery Guarding, 2025a)

2.2.4 Injury rates before and after guarding systems

Despite the irony, equipment guarding itself can cause injury. Handling heavy steel guards can cause injuries, as illustrated in Figure 10 it accounts for almost half of the guard caused injuries. Ensuring guards are the correct size and consulting specialists can prevent additional hazards. Back plates can stop reaching around guards and proper installation and continuous training can prevent guards from being removed during operation. Interlocked guards may be necessary for some applications. Lastly, guards should never be used as steps and employees should be reminded of proper guard care during safety meetings.

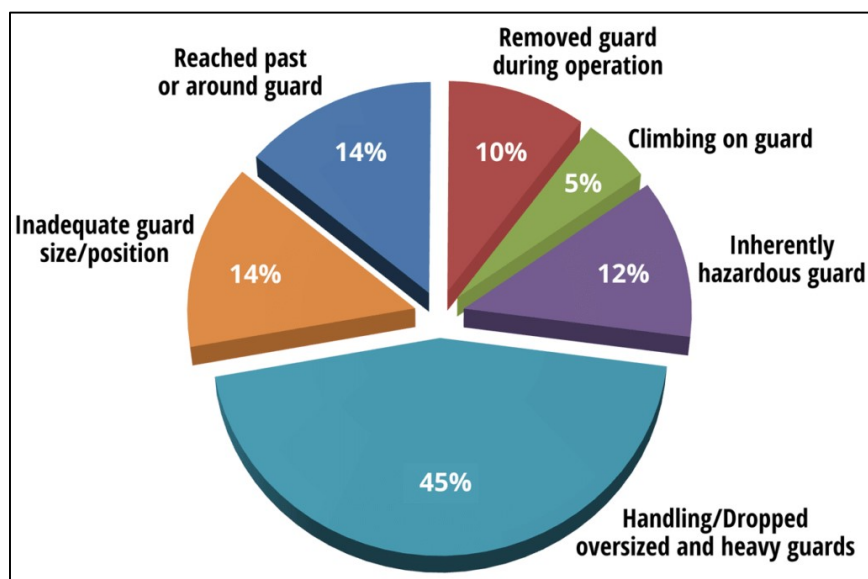


Figure 10 - Injuries Related to Guarding (Machine Guard & Cover Co., 2016)

Gaddis (2024) reports a 13–23% improvement in safety scores following the implementation of machine guarding. However, this data is drawn from small fabrication shops using primarily fixed guards. In contrast, the findings of this study suggest that adjustable interlocked guards offer greater operator acceptance and efficiency in prototyping environments where setup variability is higher. Whilst direct statistical evidence may be scarce, the consensus among organisations underscores the importance of guards in machine safety and preventing injuries (Murray, 2022).

2.2.5 Summary

Guarding systems for vertical milling machines must balance operator safety with operational efficiency. While fixed guards remain the most straightforward and compliant solution, adjustable and interlocked guards offer greater flexibility for dynamic machining environments. The pros and cons for each of these solutions can be seen below in Table 1. Future research should explore the long-term performance of self-adjusting guards and investigate strategies for cost reduction and integration into existing machinery.

Table 1 - Guarding Systems Pros & Cons

Guard Type	Pros	Cons
Fixed Guards	- Simple and reliable - Low maintenance - Provides constant protection	- Limited flexibility - Can hinder access for maintenance and
Interlocked Guards	- Automatically shuts down machine when opened - Enhances safety by preventing access to hazardous areas during operation	- Higher initial cost - Requires regular maintenance and checks
Adjustable Interlocked Guards	- Offers flexibility for different operations - Provides safety with interlocking features	- More complex to install and maintain - Potential for increased downtime due to

2.3 Relevant Enterprises

2.3.1 Sawstop

SawStop technology for power saws was introduced in 2000 with the aim of preventing severe injuries by stopping the blade almost instantly upon detecting human skin contact, see Figure 11. According to Stoll (2019), this technology has reportedly saved over 6,000 fingers. The system uses an electrical signal to sense when the blade touches skin, triggering a brake mechanism that halts the blade within milliseconds (Saving fingers with SawStop, 2005).

The widespread adoption of SawStop in both professional and amateur woodworking settings suggests its effectiveness in reducing saw-related injuries and setting a new standard for power tool safety. However, it is important to critically evaluate these claims and consider independent studies and user experiences to fully understand the impact of SawStop technology.

The technology behind SawStop is detailed in Patent US7055417B1, which was granted on June 6, 2006, to inventor Stephen F. Gass and assigned to SD3 LLC (now SawStop Holding LLC). This patent describes the mechanism that enables the rapid response of the SawStop system, including the use of a spring-loaded brake pawl that engages the blade upon skin contact (Gass, 2006).



Figure 11 - SawStop Break Mechanism (SawStop, 2025)

2.3.2 BladeStop

BladeStop, developed by Scott Technology, is an advanced safety system designed for bandsaws, primarily used in meat processing and industrial applications. Recognised globally for its rapid response time, BladeStop can halt the blade in less than 10 milliseconds upon detecting contact with an operator (Scott Automation, 2025). This system employs a dual-sensing mechanism that combines visual detection and full-body sensing to ensure maximum safety, see Figure 12. The visual system triggers a stop when an operator enters the danger zone, while the body sensing system uses a tether connected to the operator's waist to detect contact (Scott Automation, 2017).

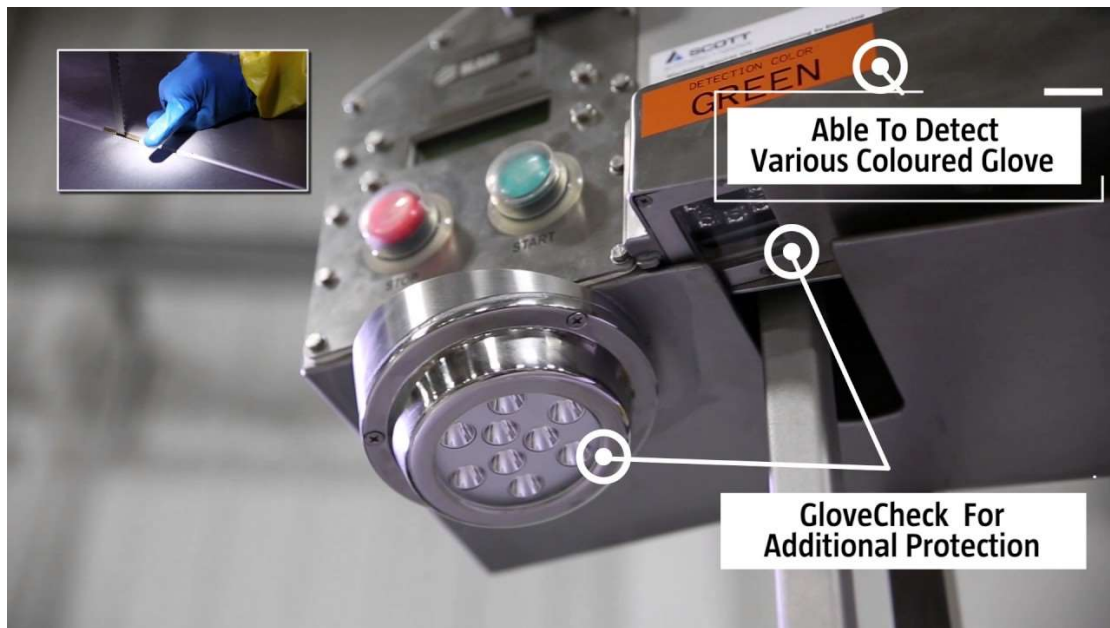


Figure 12 - BladeStop safety systems (Scott Automation, 2017)

The principles behind BladeStop's technology could be highly relevant to improving the safety of manual milling machines. Milling machines, which involve high-speed rotating tools, pose significant risks to operators. By integrating a similar dual-sensing mechanism, milling machines could benefit from rapid response, enhanced safety zones and full body sensing.

2.3.3 Summary of relevant enterprises

Companies like Renishaw could enhance the safety of manual milling machines in their manufacturing facilities by integrating advanced safety systems such as SawStop and Scott Automation's BladeStop. These technologies, which rapidly stop blades upon detecting human skin contact, could be adapted to milling machines to prevent severe injuries. By improving hazard detection and response times, Renishaw could create safer working environments, ensure compliance with safety regulations, enhance operational efficiency, and contribute to the overall productivity and sustainability of their manufacturing processes.

3 Evaluation and Final Solution

3.1 Alternative safety systems

In addition to traditional guarding methods, this section explores advanced safety systems for manual milling machines. These systems incorporate significant advancements in both hardware and software, potentially enhancing the safety of manual milling operations. By evaluating these systems, the project aims to determine their effectiveness in improving hazard detection and response, thereby reducing the risk of accidents and injuries. Moreover, these systems contribute to increased operational efficiency and ensure compliance with evolving safety regulations. Integrating these solutions could not only improve operator protection but also enhance the overall productivity and user comfort.

3.1.1 Passive infrared sensors (PIR)

PIR sensors are widely used for occupancy detection, as shown in Figure 13, motion sensing, and security systems by detecting infrared radiation emitted by objects (Wu et al., 2020). They are valued for their cost-effectiveness, low power consumption, and privacy-preserving nature. Recent advancements have enhanced their sensitivity and accuracy, particularly through integration with machine learning algorithms, making them notable in smart buildings for occupancy monitoring and energy management (Shokrollahi et al., 2024). However, PIR sensors face challenges such as limited range and sensitivity to environmental conditions like temperature and humidity. In vertical milling machines, PIR sensors could be integrated to detect the presence of operators and trigger the emergency brake to prevent injuries, similarly to how they prevent collisions in robotics (Ismail, Omar and Suaibun, 2016).

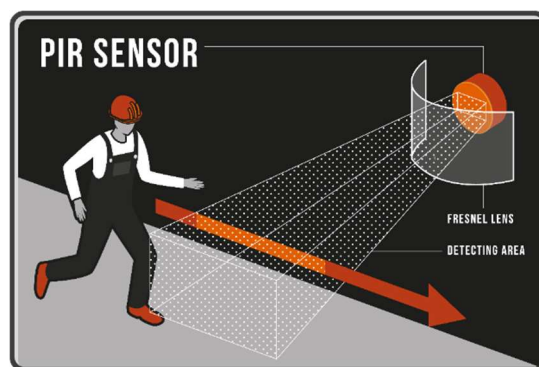


Figure 13 - PIR Sensor Application (Contin Technology, 2025)

3.1.2 Light curtains

Light curtains are optoelectronic devices used for safety and automation in industrial settings, creating an invisible barrier with an array of light beams that trigger a response, such as stopping machinery when interrupted, as illustrated in Figure 14. According to Lu and Seiichi Serikawa (2013) light curtains provide a reliable and cost-effective solution for protecting operators from accessing hazardous areas. Modern advancements have improved their resolution and response time, making them dependable for detecting small and fast-moving objects.



Figure 14 - Light Curtains (Association for Advanced Automation, 2024)

Despite their advantages, Rowse (2019) notes that one of the most common issues with light curtains is their proximity to the hazard. To be effective, light curtains must be positioned at a sufficient distance from the dangerous area to ensure that the hazardous process can be halted before a person can reach it in the event of an intrusion. Dust, smoke, and ambient light can also affect light curtains, requiring regular maintenance and calibration. Similarly, Orlosky (2021) highlights that light curtains may malfunction in environments with high levels of particulates or reflective surfaces, suggesting that alternative safety measures might be more suitable in such conditions. This is attributed to the technology rather than the equipment; a demonstration video published by Keyence Corporation (2012) shows light curtains operating perfectly reliably after being fully submerged underwater for one month.

Research shows that making intelligent safety choices is crucial as machinery safety standards evolve. This provides valuable insights for the milling machine safety project by

guiding the selection and implementation of effective light curtain systems to enhance operator safety (Lazzara, 2003). If integrated with vertical milling machines, the light curtains could prevent startup or shutdown if the correct settings are not met, i.e. operator's hand is near the dangerous area. However, due their size and nature these could be obtrusive and interfere with operator efficiency. There is also a concern that false positives may occur when machining with coolant or larger amounts of swarf.

3.1.3 Capacitive proximity sensors

Capacitive sensors detect changes in capacitance caused by the presence or movement of an object, making them versatile for applications like touchscreens, proximity sensing, and level detection. Capacitive sensors use electric fields to detect contactless object such as the human body (Ye et al., 2018). Figure 15 shows how these sensors are used in robotics to avoid human collisions. Despite their susceptibility to environmental factors such as humidity and temperature, ongoing research aims to improve their reliability through better design and signal processing. According to the research (Haslinger and Zagar, 2016) this technology can be used to detect movement in human fingers. In vertical milling machines, this technology could be used to detect an operator's hand near moving parts and trigger the emergency brake to prevent injuries.

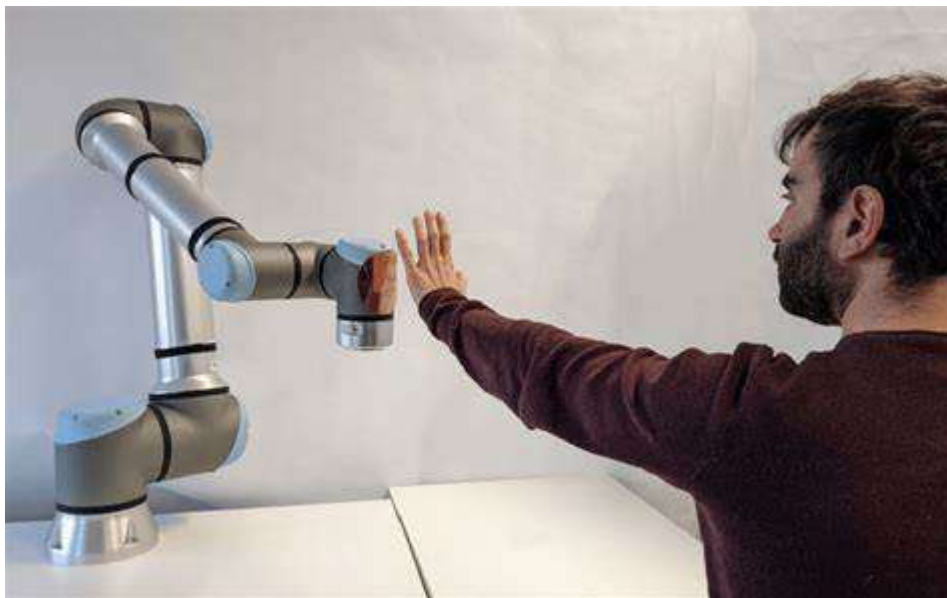


Figure 15 - Capacitive Proximity Sensor used in Robotics (Alagi et al., 2022)

3.1.4 Camera systems

Camera systems are increasingly being used for safety and monitoring in industrial settings, as shown in Figure 16. These systems can provide real-time visual monitoring of the milling machine's operation, allowing for immediate detection of unsafe conditions. According to the research (Shu and Shu, 2021) multiple cameras were used to create a fall detection system using human fall pattern recognition via machine learning. This demonstrates the potential of integrating advanced camera systems and machine learning algorithms to enhance safety, which can be applied to improving the safety of vertical milling machines by detecting and preventing hazardous situations. However, they require proper lighting and can be affected by environmental factors such as dust and glare.



Figure 16 - AI Machine Vision System (Keyence, 2025)

3.1.5 Conductive sensors

Conductive sensors are critical components in enhancing safety and precision in various applications. These sensors operate by measuring changes in electrical conductivity when conductive material such as human skin contacts the sensor surface (Allen, 2023). Human skin has distinct electrical properties, such as resistance and capacitance, which these sensors can detect and process. This technology is widely used in safety mechanisms for power tools, such as table saws, where the sensor can trigger an immediate stop to prevent injury upon detecting skin contact (Harris, 2024). Additionally, conductive sensors are employed in medical devices that require accurate interaction with human skin, such as wearable sensors for monitoring vital signs and diagnostic equipment (Cao et al., 2024).

In the context of manual milling machines, the integration of conductive sensors for flesh detection could significantly reduce injury severity. By incorporating flesh-detection sensors,

the machine could automatically halt operation if it detects human skin near the cutting tool, thereby preventing accidents or significantly reducing their severity. Despite their advantages in safety and precision, challenges such as distinguishing between human flesh and other materials and the cost of high-precision sensors remain. Overall, conductive sensors for flesh detection represent a significant advancement in safety technology, offering reliable and immediate responses to potential hazards.

3.1.6 Pressure-sensitive safety mats

Pressure mats are safety devices designed to detect the presence of personnel in hazardous areas around machinery. When someone steps on the mat, it sends a signal to stop the machine, preventing accidents and injuries, or they can be reversed to detect someone moving from a mat. These mats are exceptionally durable, resistant to wear and environmental factors, and can be customised to fit various industrial applications, shown in Figure 17. By providing an immediate response to potential hazards, pressure mats significantly enhance workplace safety. For manual milling machines, pressure mats can be used to ensure the machine stops if an operator steps into a dangerous zone, thereby preventing accidental contact with moving parts (Rockford Systems, 2025).

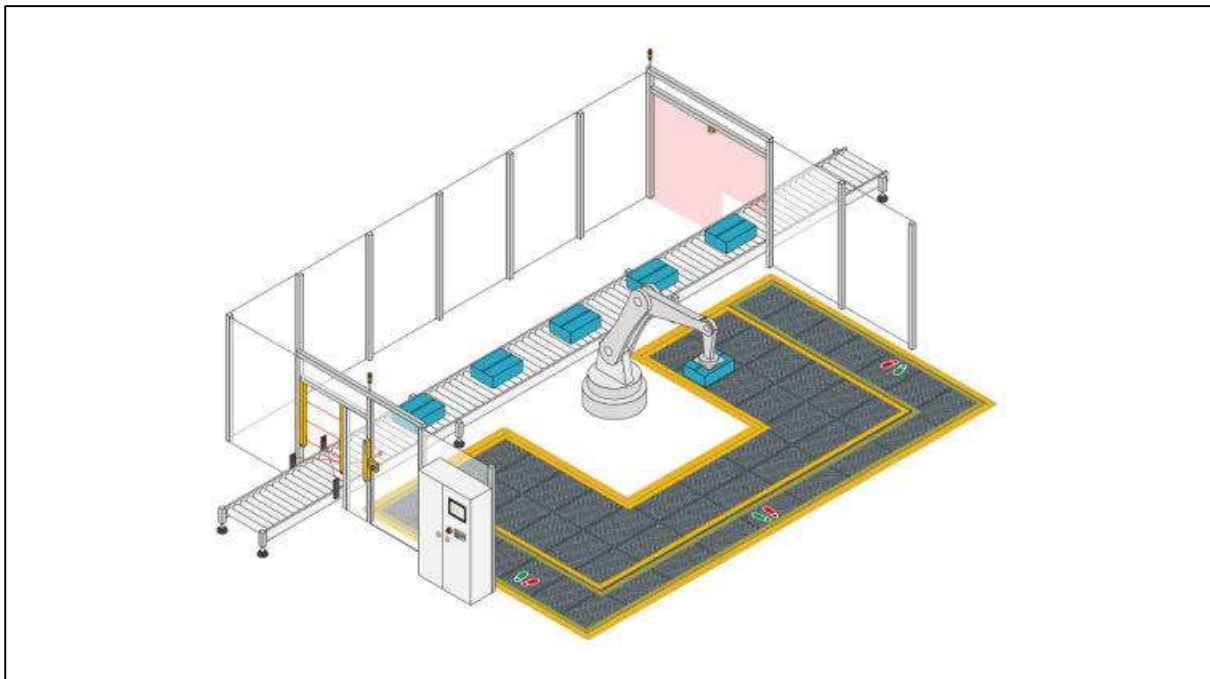


Figure 17 - Pressure mat application (Prime Automation, 2017)

3.1.7 Summary

Integrating alternative safety technologies, such as PIR sensors, light curtains, capacitive proximity sensors, camera systems, conductive sensors and pressure mats, could significantly improve the safety of manual milling machines. Each sensor type offers unique advantages and faces specific challenges, making them suitable for different aspects of safety improvement. By combining current solutions with these alternative technologies, it is possible to create a safety framework that effectively protects operators and reduces the risk of injuries.

3.2 Evaluation of potential safety systems

In the context of improving the safety of vertical milling machines, it is essential to employ decision-making tools to ensure that the chosen safety systems are both effective and dependable. Two such tools, Failure Mode and Effects Analysis (FMEA) and the Multi-criteria decision analysis (MCDA), are particularly valuable in this process. These tools help evaluate potential safety solutions, considering several factors such as reliability, cost, and ease of integration, thereby facilitating informed and unbiased decision-making.

3.2.1 Failure Mode and Effect Analysis (FMEA)

FMEA is a systematic approach used to identify potential failure modes for a product or within a system, assess their impact, and prioritise actions to mitigate risks. Originating in the US military in the 1940s (Huber, 2024), FMEA has since been widely adopted across various sectors, including automotive, manufacturing, and healthcare, due to its effectiveness in enhancing reliability and safety (Woodhouse, 2005). By systematically evaluating each component and its potential failure modes, FMEA helps in understanding the severity, occurrence, and detectability of failures, which are quantified using the Risk Priority Number (RPN). This method is particularly useful in projects aimed at integrating modern safety systems into manual milling machines.

For instance, when deciding which safety system to implement, FMEA can be employed to compare the potential failure modes of each sensor type. By analysing factors such as failure rates, detection capabilities, and the severity of potential failures, FMEA can aid in selecting the most reliable and effective sensor for enhancing machine safety (Sartor and Orzes, 2019). This structured approach ensures that the chosen sensors not only meet the

safety requirements but also contribute to the overall reliability and efficiency of the milling machine.

This FMEA was conducted by the author and another colleague, both of whom have extensive experience in manual machining. Their practical knowledge in the field qualifies them to accurately rank and evaluate the safety technologies, ensuring that the recommended actions are both relevant and feasible. This evaluation tool will guide the selection and implementation of the most effective safety measures, ultimately contributing to a safer working environment.

Table 2 - Failure Mode and Effect Analysis

FMEA for Manual Vertical Milling Machine												
Item	Function Requirements	Failure Mode	Effect(s) of Potential Failure	Severity	Potential Causes of Failure	Occurrence	Current Design Controls (Prevention)	Current Design Controls (Detection)	Detection	RPN	Total RPN	Recommended Action(s)
Adjustable Interlocked Guard	Prevent access to dangerous areas	Interlock failure	Increased risk of accidental contact with moving parts	8	Lack of training, inadequate supervision	3	Tamper resistant features, training and awareness	Safety relay & audible indicator	3	72	144	Multiple safety layers and regular maintenance
		Deliberate Override	Increased risk of accidental contact with moving parts	8	Poor design, operator overcompetancy	3	Tamper resistant features, training and awareness	Safety relay & audible indicator	3	72		Multiple safety layers and regular maintenance
PIR Sensor	Detect human presence	Sensor fails to detect presence	Increased risk of accidental contact with moving parts	8	Sensor malfunction, obstruction, power failure	3	Regular maintenance, clear installation area	Self-diagnostic feature, periodic testing	5	120	220	Implement redundant sensors, improve diagnostic algorithms
		False detection (detects when no one is present)	Unnecessary machine stoppage	5	Environmental interference, sensitivity issues, swarf	4	Calibration, environmental shielding	Sensitivity adjustments, environmental monitoring	5	100		Improve calibration procedures, enhance shielding
Light Curtain	Detect interruption	Light curtain fails to detect interruption	Increased risk of accidental contact with moving parts	9	Misalignment, dirt on sensors, electrical issues	2	Regular cleaning, alignment checks	Status indicators, regular testing	4	72	216	Enhance cleaning protocols, use more robust alignment mechanisms
		False interruption detection	Unnecessary machine stoppage	6	Environmental interference, sensitivity issues	6	Calibration, environmental shielding	Sensitivity adjustments, environmental monitoring	4	144		Improve calibration procedures, enhance shielding
Capacitive Proximity Sensor	Detect presence of objects or humans	Sensor fails to detect proximity	Increased risk of accidental contact with moving parts	7	Sensitivity issues, environmental interference	4	Calibration, environmental shielding	Calibration checks, environmental monitoring	5	140	240	Improve calibration procedures, enhance shielding
		False detection (detects when no object is present)	Unnecessary machine stoppage	5	Environmental interference, sensitivity issues	4	Calibration, environmental shielding	Sensitivity adjustments, environmental monitoring	5	100		Improve calibration procedures, enhance shielding
Camera System	Monitor machine surroundings and detect human presence	Camera fails to capture or transmit images	Increased risk of accidental contact with moving parts	8	Lens obstruction, software glitches, power issues	3	Regular cleaning, software updates, power backup	Image quality checks, system diagnostics	4	96	168	Implement redundant systems, enhance software reliability
		False image capture (incorrect data)	Unnecessary machine stoppage	6	Software glitches, environmental interference	3	Software updates, environmental shielding	System diagnostics, image quality checks	4	72		Enhance software reliability, improve shielding
Conductive Sensor	Detect contact with conductive materials	Sensor fails to detect contact	Increased risk of accidental contact with moving parts	7	Wear and tear, electrical interference	3	Regular inspection, shielding	Continuity testing, system diagnostics	5	105	180	Enhance inspection protocols, improve shielding
		False detection (detects contact when none exists)	Unnecessary machine stoppage	5	Sensitivity issues, environmental interference	3	Calibration, environmental shielding	Sensitivity adjustments, environmental monitoring	5	75		Improve calibration procedures, enhance shielding
Pressure mats	Detect human presence	Sensor fails to detect presence	Increased risk of accidental contact with moving parts	7	Wear and tear, electrical interference	3	Regular inspection, shielding	Continuity testing, system diagnostics	5	105	165	Enhance inspection protocols, improve shielding
		Sensor fails to detect presence	Increased risk of accidental contact with moving parts	5	Sensor malfunction, obstruction, power failure	3	Regular maintenance, clear installation area	Self-diagnostic feature, periodic testing	4	60		Implement redundant sensors, improve diagnostic algorithms

As shown in Table 2, the analysis highlights critical issues such as increased risk of accidental contact with moving parts and unnecessary machine stoppage. Recommended actions include implementing redundant systems, enhancing calibration procedures, improving shielding, and regular maintenance. This systematic approach aims to enhance the reliability and effectiveness of safety measures in milling environments. To aid interpretations Figure 18 presents a radar chart showing the lower scoring systems closer to the centre of the chart.

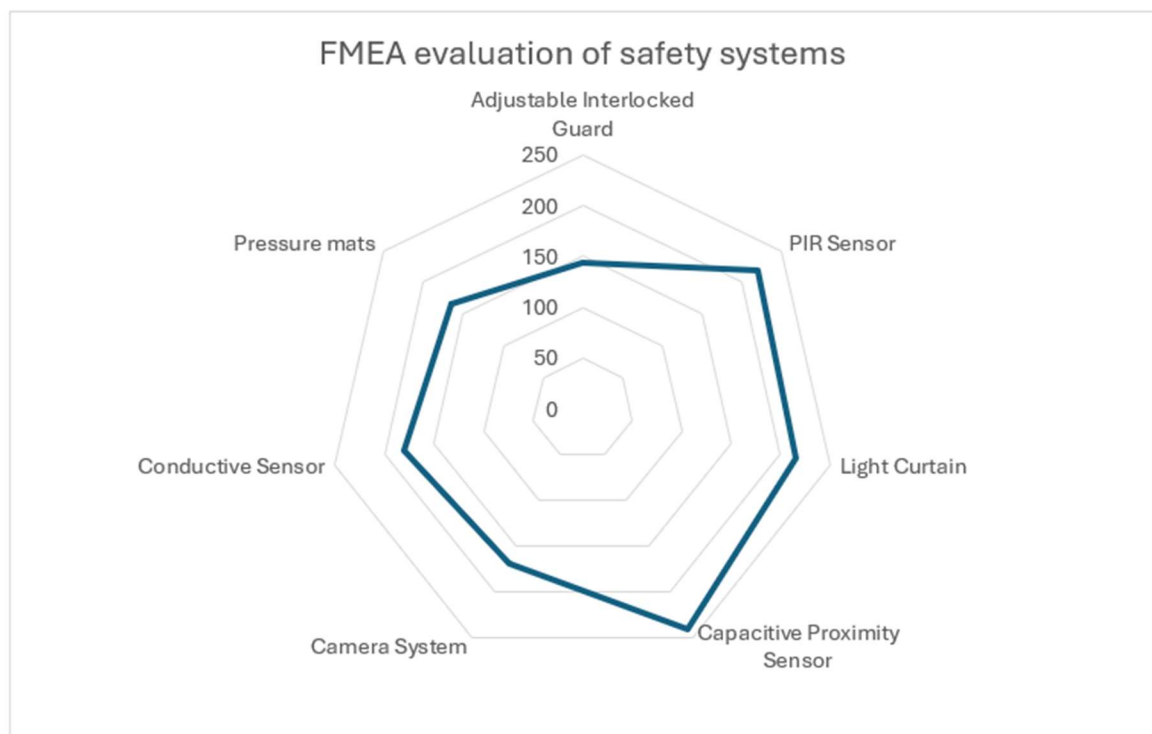


Figure 18 - FMEA Radar chart

3.2.2 Multi-Criteria Decision Analysis (MCDA)

Multi-Criteria Decision Analysis (MCDA) is a structured method for evaluating and prioritising multiple options based on a set of weighted criteria. It is particularly useful in complex decision-making scenarios where technical, economic, and practical factors must all be considered. The process involves identifying relevant options and evaluation criteria, assigning importance weights to each criterion, and scoring each option accordingly. The weighted scores are then aggregated to produce a ranked list of alternatives, providing a transparent and rational basis for decision-making (Basílio et al., 2022).

In the context of enhancing the safety of manual milling machines, MCDA enables the systematic comparison of modern sensor-based safety technologies. Key evaluation criteria for this application included reliability, cost, ease of integration, detection accuracy, maintenance requirements, user training needs, durability, false positive and false negative rates, operator acceptance, and impact on productivity. Sensor technologies considered in the analysis included passive infrared (PIR) sensors, light curtains, capacitive proximity sensors, camera systems, and conductive sensors.

The MCDA matrix was developed by the author, a development machinist, using domain-specific knowledge to score each technology against the defined criteria. This ensured that practical considerations from a workshop environment were reflected in the evaluation. The results allowed for an evidence-based selection of technologies that offer the greatest benefit in terms of safety performance and ease of implementation.

Table 3 - Multi-Criteria Decision Analysis

Criteria	Weight	Safety Technology						
		Adjustable Interlocked Guards	Passive Infrared Sensors	Light Curtains	Capacitive Proximity Sensors	Camera Systems	Conductive Sensors	Pressure Mat
Initial Cost	10	7	6	4	7	3	7	8
Maintenance Cost	10	7	7	6	6	5	4	8
Detection Accuracy	15	6	4	9	6	8	3	9
Ease of Integration	10	5	5	6	4	3	2	5
User Training Requirements	5	7	8	8	8	5	8	6
Durability	10	8	5	3	5	3	4	8
False Positive (Accidental Detection)	10	7	2	3	2	7	3	7
False Negative Rate (No Detection)	10	7	5	6	3	7	6	7
Impact on Productivity	10	8	8	7	8	6	8	8
Operator Acceptance	5	8	8	5	8	4	8	8
Effectiveness in working Environment	5	7	2	3	4	4	3	7
Total Score:		690	530	565	540	525	480	750

As shown in Table 3, pressure mats and adjustable interlocked guards scored highest, particularly excelling in detection accuracy, durability, and minimal impact on productivity. Conductive sensors, by contrast, scored lowest, primarily due to concerns over reliability and integration complexity. This analysis highlights both the relative strengths and weaknesses of each technology and supports informed selection based on project-specific requirements.

To further aid interpretation, Figure 19 presents a bar chart that visualises the performance of the top technologies across key criteria. The interlocked guard shows consistently strong scores across all categories, while the underperformance of the conductive sensor is immediately apparent. This visual supplement reinforces the matrix findings and supports the final decision to prioritise interlocked guards for implementation.

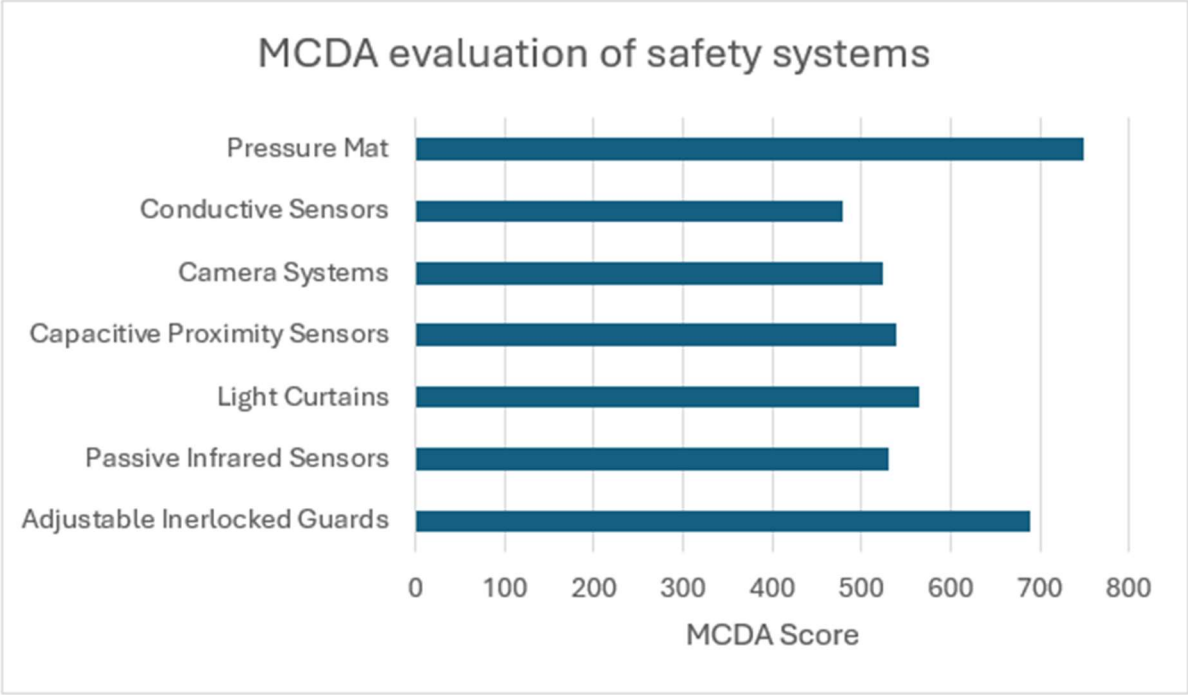


Figure 19 - MCDA Bar chart

3.3 Final Solution

It was evident that the adjustable interlocked guard and pressure mats scored highly in the FMEA and MCDA, therefore these systems would be pursued further. Discussions were held with the electrical engineering team at Renishaw to determine if the two best options were viable. As Figure 20 shows, it was suggested that the pressure mats be installed after the interlocked guards due to ease of integration.

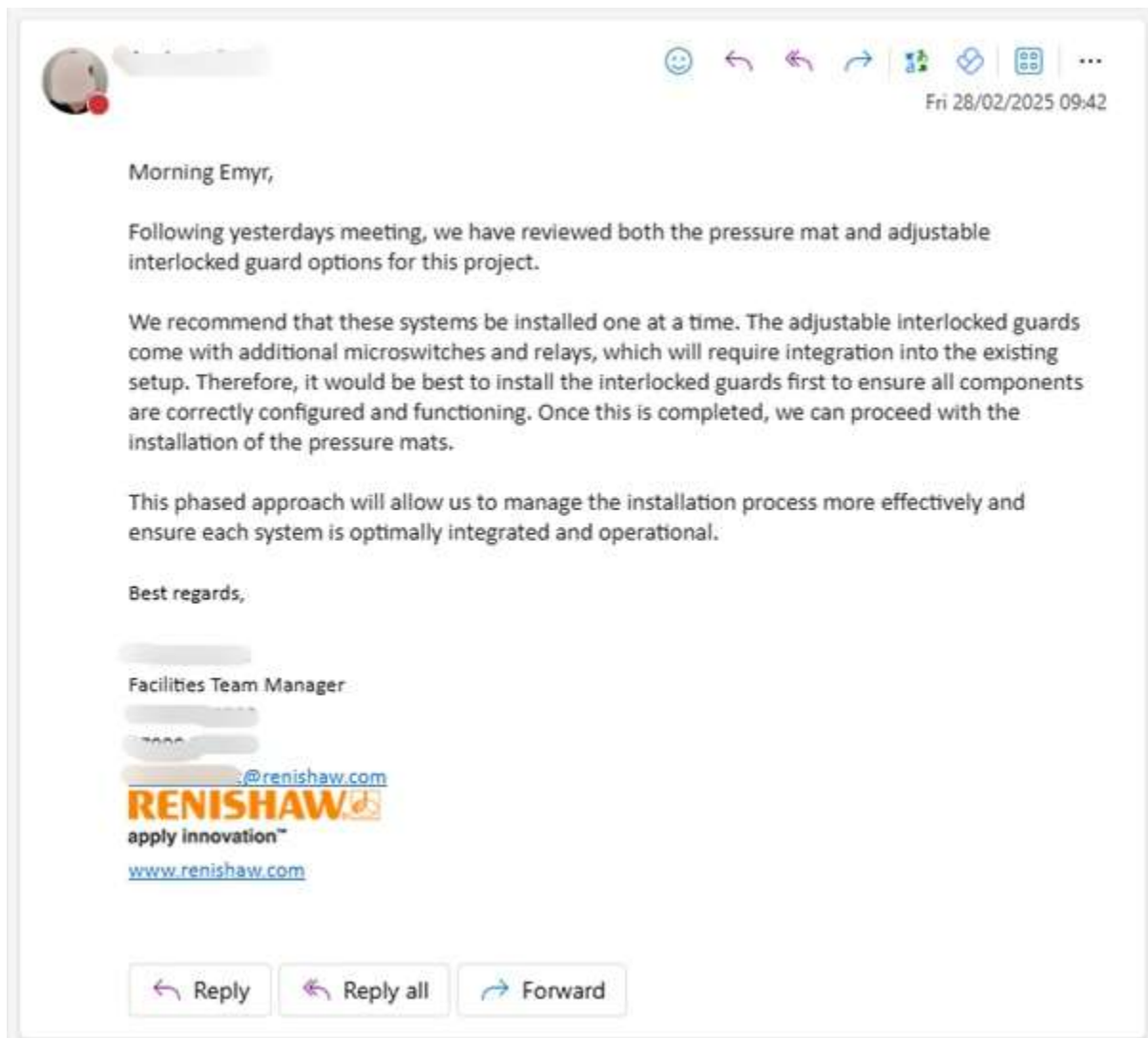


Figure 20 – Communication outlining recommendations (with redactions for confidentiality)

Additionally, suppliers of interlocked guarding offered installation packages, whereas pressure mat suppliers did not. Given the time frame from this project, only one of these systems could be installed, therefore, the system with the most added value was chosen. This was the adjustable interlocked guards as they physically prevent access to rotating parts, whereas the pressure mats do not.

These analyses highlighted their ability to mitigate risks and meet the project's safety and operational requirements. Camera systems and light curtains, while also effective, did not score as highly in these assessments.

Consultations with the electrical engineering team at Renishaw provided valuable insights into the practical implementation of these systems. The team recommended a phased installation approach, starting with the pressure mats and then moving on to the interlocked guard, or vice versa. This approach would allow for a more manageable integration process and ensure that each system could be thoroughly tested and optimised before the next was installed.

One significant advantage of the interlocked guarding was the availability of installation packages from suppliers. This not only simplified the installation process but also ensured that the system was set up correctly and met all safety standards. In contrast, pressure mat suppliers did not offer such packages, which could potentially complicate the installation and increase the risk of errors.



Figure 21 - Adjustable interlocked milling machine guard

Given the project's time constraints, it was crucial to select the system that would provide the most immediate and significant benefits. The adjustable interlocked guards were chosen because they offer a physical barrier that prevents access to hazardous rotating parts, providing a higher level of safety compared to pressure mats, see Figure 21. Pressure mats, while effective in detecting presence and preventing operation, do not offer the same level of physical protection.

In conclusion, the decision to install the adjustable interlocked guards was based on their superior safety features, the availability of installation support, and the practical

considerations of the project's timeline. This choice ensures that the most critical safety measures are in place, reducing the risk of accidents and enhancing the overall safety of the operation. The final configuration following installation is presented in Figure 22.

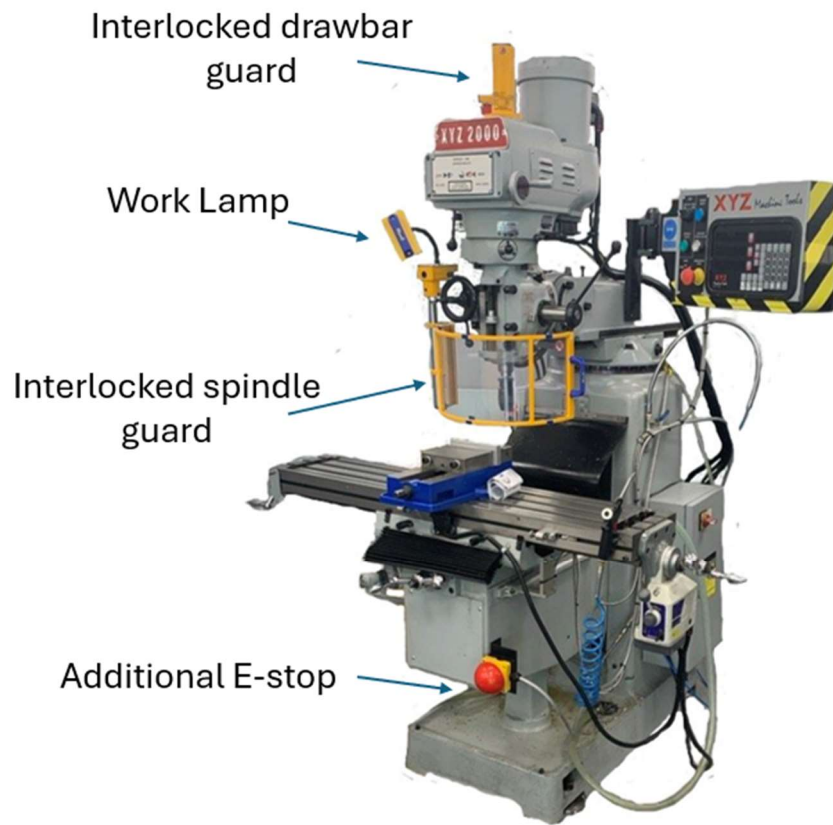


Figure 22 - Milling machine after installation

4 Purchasing and Installation

This section details the procurement and budget management aspects of the project, providing transparency about the materials and equipment acquired. It demonstrates budget management and justifies the choices made, explaining how each purchase contributes to the project's success. Additionally, it acknowledges any financial support received, ensuring accountability and recognizing contributions. Overall, this section highlights the importance of strategic resource allocation and financial planning in achieving the project's objectives.

4.1 Budget

A budget of £3570 was approved for this project following a thorough procurement process. Multiple quotes from suppliers were obtained to ensure the budget was sufficient. The justification for this expenditure was based on a risk assessment that highlighted the need for guarding the milling machine's drawbar and spindle. The budget request was submitted on 17/02/2025 and received full approval from the area manager, higher management, and the finance department by 03/03/2025.

4.2 Vendor Selection

Companies not on Renishaw's list of approved vendors require rigorous inspections that consume considerable amounts of time. Therefore, unless a vendor significantly stood out in terms of cost or quality, a supplier from the list of approved vendors would need to be used. Due to Renishaw's strict purchasing policies, only one vendor could supply the requested guarding: Machine Covers Ltd, based in Gloucestershire. Machine Covers Ltd specialises in providing safety solutions for industrial machinery and is the official UK distributor for Repar2, a well-known international guarding supply company. A quotation was obtained from Machine Covers Ltd, amounting to £3417.95, including installation by qualified technicians. Given the company's reputable standing and expected quality, they were selected to supply the guarding for this project.

4.3 Procurement Timeline

The procurement timeline reveals varying durations for different steps, see Figure 23. Raising the Capital Expenditure Allowance (CEA) on 17/02/2025 and its approval by 03/03/2025 took about two weeks, a standard period for budgetary reviews. The Purchase Requisition, raised on 04/03/2025 and approved the next day, 05/03/2025, was processed swiftly, indicating efficient internal procedures. Similarly, the Purchase Order was created promptly on 06/03/2025. However, the vendor's promised supply date of 14/04/2025 introduced a longer waiting period of over a month, likely due to manufacturing and shipping logistics. This highlights the efficiency of internal processes and the variability in external supply chain dynamics. University of Texas at Arlington (2018), procurement timelines can vary significantly based on factors such as budget issues, vendor document reviews, and the complexity of the procurement process. Although the vendor initially agreed to supply the items by 14/04/2025, they installed the guarding earlier than expected on 24/03/2025, demonstrating exceptional service and efficiency.

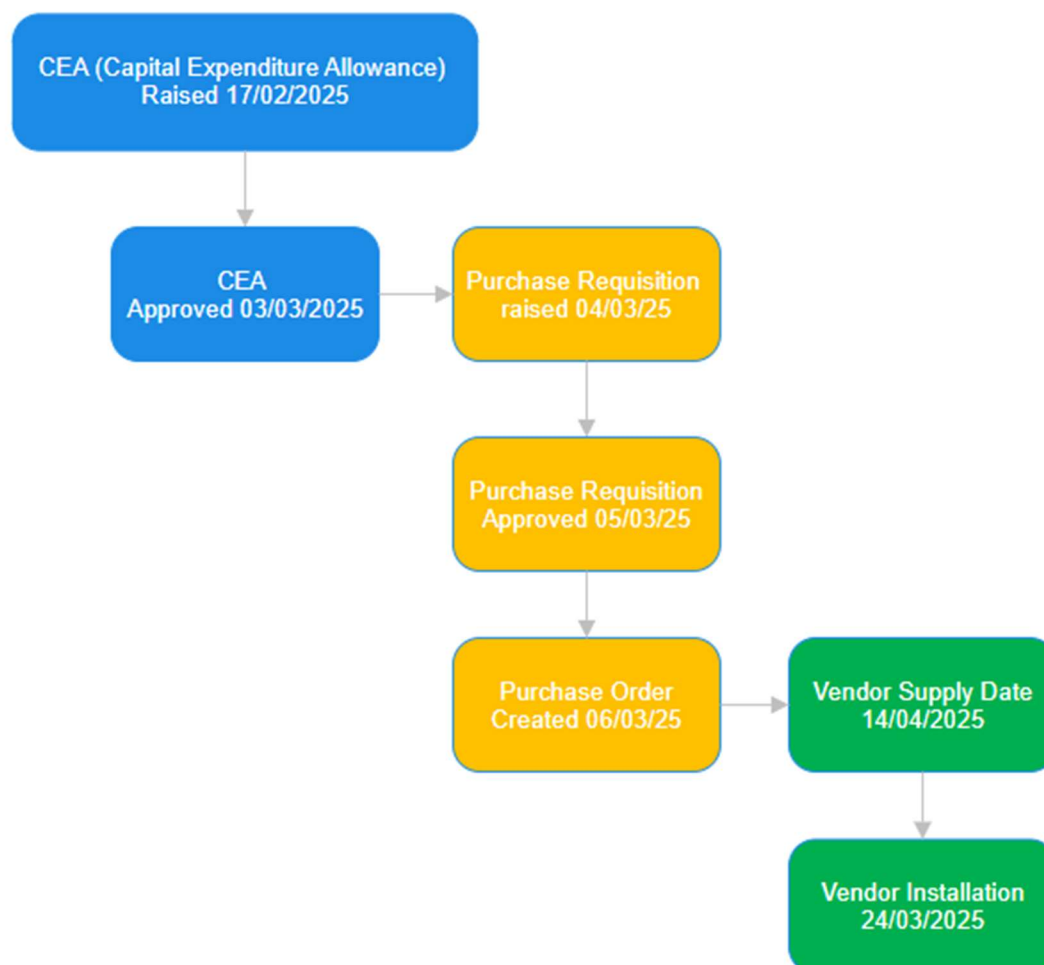


Figure 23 - Procurement timeline flow chart

5 Testing and Validation

5.1 Methodology

This section presents the procedures and outcomes of the testing and validation phase undertaken to assess the effectiveness of the implemented safety enhancements on a vertical milling machine. The primary objectives were to verify the mechanical robustness and functional reliability of the safety features, and to evaluate their impact on operator efficiency and potential cost savings.

5.2 Stress and Abuse Testing in Accordance with ISO 14120

The objective of this testing is to verify that the guarding systems can withstand mechanical stress and abuse during normal and foreseeable use, without compromising their protective function. This testing will be designed in accordance with ISO 14120 (General requirements for the design and construction of fixed and movable guards). This standard outlines the necessary performance criteria for guards intended to protect users from mechanical hazards, these criteria can be seen in Figure 24.

5.4	Materials, rigidity, and impact requirements	13
5.4.1	General.....	13
5.4.2	Impact and ejection resistance.....	13
5.4.3	Rigidity.....	13
5.4.4	Secure fixing.....	13
5.4.5	Reliability of moving parts.....	13

Figure 24 - Guard requirements (International Organization for Standardization, 2015)

The testing will be conducted with the new guard permanently installed; however, it will be swivelled out of the way during tests involving the old guard. The old guard can be mounted and tested without interfering with the new guard system. This arrangement is illustrated in Figure 25, where the new guard system is shown to the left and the old guard system fitter to the table.

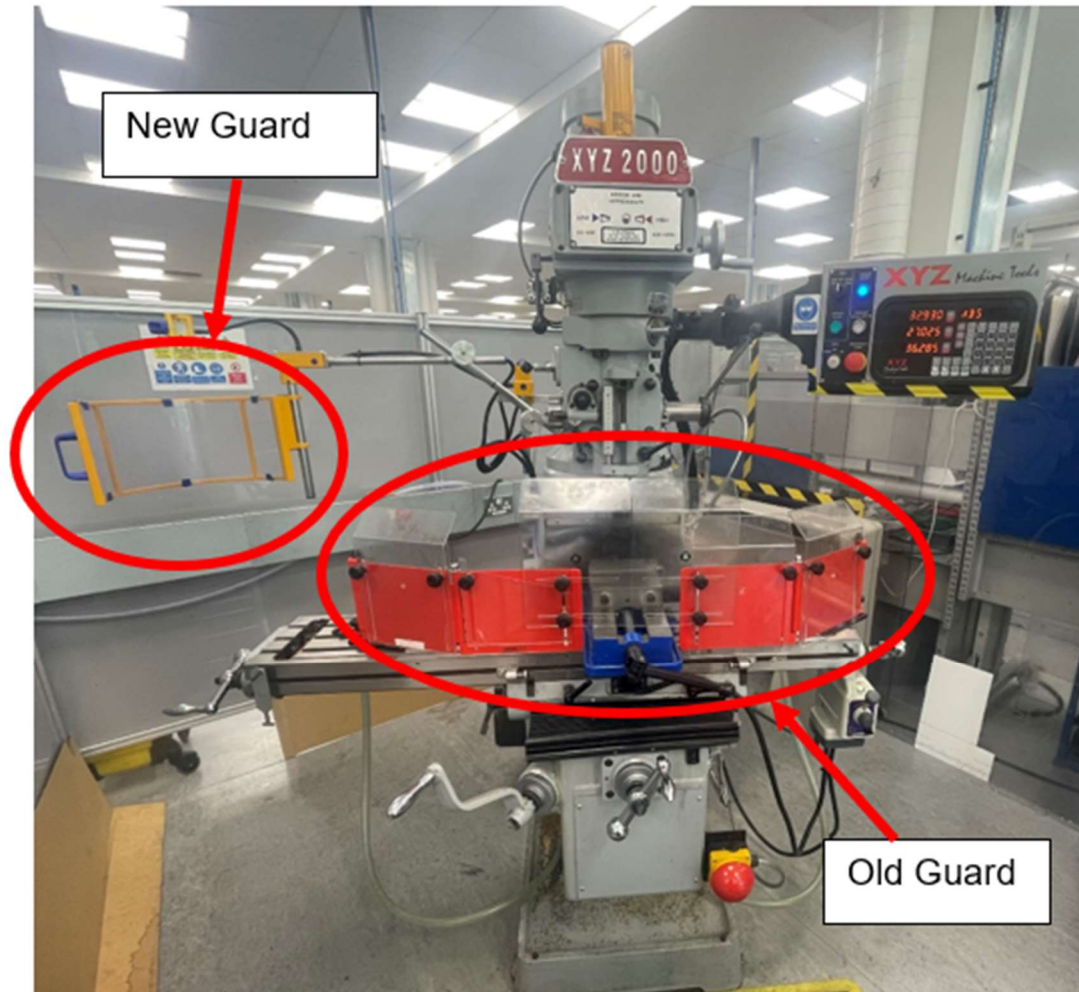


Figure 25 - Guard Testing setup

5.2.1 Impact and rigidity test

This test employed a weighted pendulum suspended from a rope of known length, released from the horizontal position to deliver a specific impact force. As noted by Kravchuk et al. (2022), pendulums are a conventional and reliable method for conducting impact tests. This approach is essential to verify that the guard can withstand accidental impacts, such as those caused by operators leaning or falling against it, as well as from material ejected during machine operation.



Figure 26 - Impact test measurement setup

Displacement resulting from the impact was measured using a camera to capture the highest value shown on the digital plunger indicator shown in Figure 26, with a measurement scale provided by a rule placed beneath the guard. To generate the impact force, a 250gram pendulum was attached to a 500 mm massless rope and released horizontally from a frictionless pivot located 500 mm directly above the guard as shown in Figure 27. This ensured that the pendulum reached its equilibrium position at the point of contact.

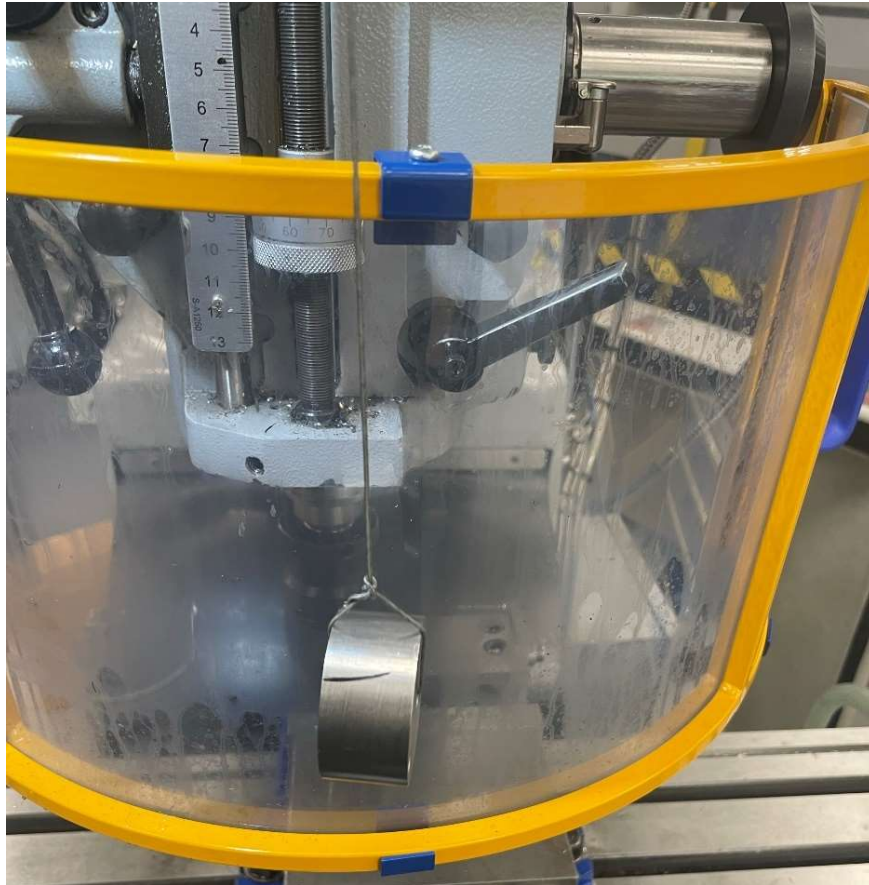


Figure 27 - Pendulum setup

Each guard was subjected to ten impacts, and the resulting data were recorded via the camera. It's important to note that using a camera to read the dial indicator depends on how carefully the person reviews the footage. This means the accuracy of the results can vary slightly depending on who is taking the readings.

Pendulum Impact Test		
Test Number	New Guard Displacement	Old Guard Displacement
1	14.8	16.3
2	15.2	17.2
3	15	16.5
4	14.9	16.4
5	15.1	16.6
6	15.3	16.8
7	15	16.5
8	14.7	16.2
9	15.4	17.4
10	15	16.5

Figure 28 - Pendulum Impact Test Results

The results shown in Figure 28 measured across 10 impacts show that the mean displacement for the new guard type was 15.04mm, while the old guard type averaged 16.64mm, indicating greater displacement under identical conditions. Maximum displacements ranged from 17.4mm for the old guard to 15.4mm for the new guard.

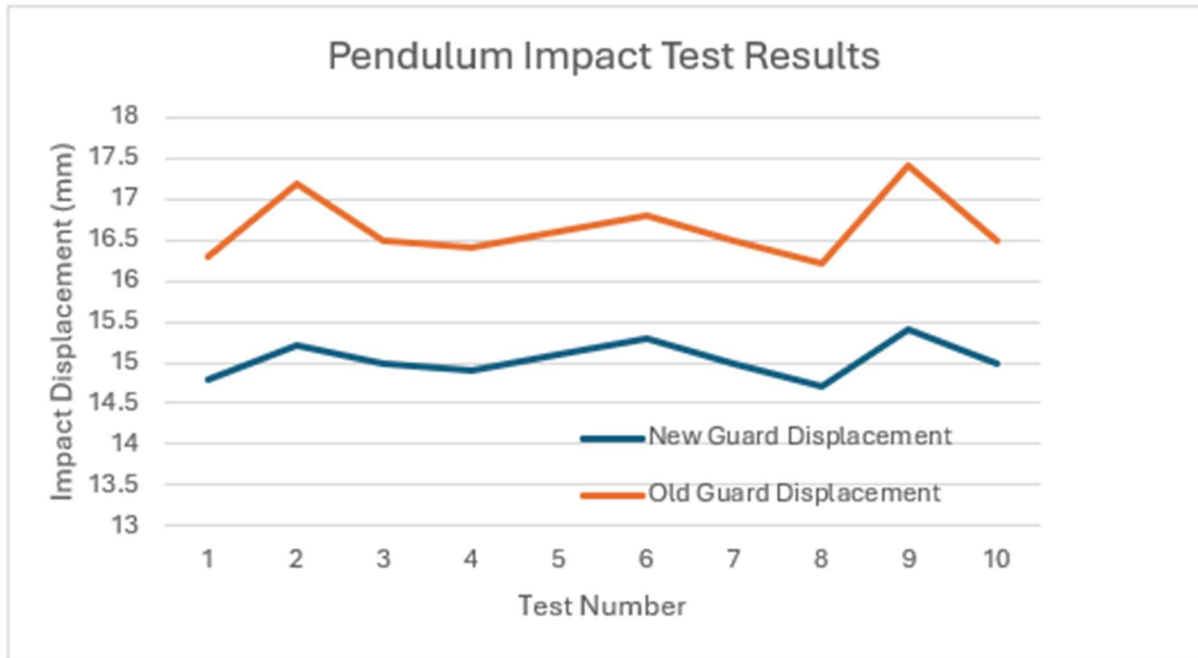


Figure 29 - Pendulum Impact Test Graph

As illustrated in Figure 29, the results suggest that the new guard offers superior structural integrity and is better suited for environments where reliable impact resistance is critical. The observed difference in movement is likely due to the geometry of the newer guard system, which is narrower than the old one. As a result, the point of impact is positioned closer to the hinge. When a force is applied closer to the pivot point, the resulting torque is reduced, but the hinge experiences greater resistance to movement due to the shorter moment arm. This increased resistance torque limits the displacement of the guard during impact. This relationship between torque, force, and distance from the pivot is well-established in mechanical engineering and is supported by studies on hinge mechanics and rotational stiffness such as the one by Wang et al. (2023).

5.2.2 Reliability of moving parts

In accordance with ISO 14120:2015, all moving parts of guards must be designed to ensure long-term reliability and consistent performance under normal operating conditions. This includes components such as hinges, latches, and adjustable elements, which must

maintain their function without degradation over time. The standard emphasises that guards should resist loosening, misalignment, or failure due to repeated use, vibration, or environmental factors.

The new guard system incorporates small grub screws to allow for fine adjustment of the guard height, see Figure 30. While this provides flexibility during installation and setup, the use of such small fasteners introduces a potential reliability concern. Due to their limited thread engagement and size, these grub screws may be susceptible to overtightening, which could result in stripped threads or reduced holding strength over time. This could compromise the guard's ability to maintain its intended position, especially under mechanical stress or vibration.



Figure 30 - New spindle guard grub screws

According to the research (Eccles, 2005) the coefficient of friction doubles by the tenth re-tightening of a threaded fastener due to increased friction. The research also states that due to the increased friction the clamping force provided by the fastener decreases for a given torque, this can be seen in Figure 31.

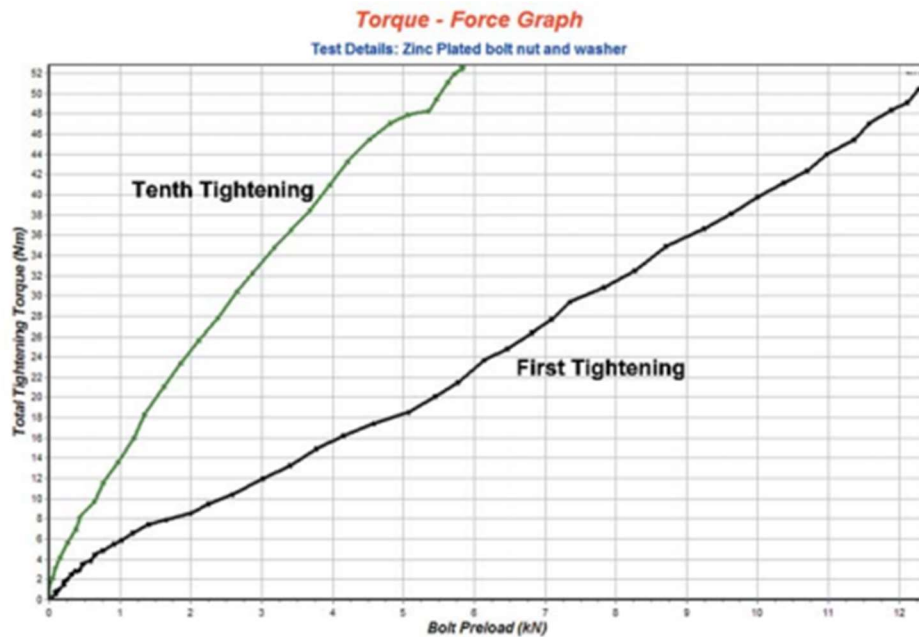


Figure 31 - Threaded fastener re-use (Eccles, 2005)

5.3 Operator Efficiency Testing

This section aims to measure the efficiency of the new guarding system compared to the old system. Throughout these tests, the existing guarding is referred to as the "old" guard, while the newly purchased system for this project is termed the "new" guard. Four tests were conducted to simulate the most common tasks an operator would face. These tests were carried out by five operators with similar levels of experience.

The first test focused on part loading, simulating the process of loading material into the vice for machining and its subsequent removal post-machining. To ensure fairness, the same material was used for each test. The test began with the vice fully closed and the guards shut, as illustrated in Figure 32. The operators were instructed to open the guard, open the vice, secure the part in the vice, and then close the guard. Each complete cycle of these actions counted as one repetition out of ten. The times taken for each repetition with both guarding types were recorded and are shown in Table 4. The results indicate that the new guard is 49% faster than the old guard. This increased efficiency is likely attributed to the new guard's design, which features a single door compared to the old guard's two doors. This streamlined design significantly reduces the time required for opening and closing, resulting in nearly a 50% improvement.



Figure 32 - Old Guard (left) vs New Guard (right) Vice Test

The second test focused on tool changes, measuring the impact of the guards on swapping tooling in the spindle. The test began similarly to the vice test, with no tooling in the spindle and the guards closed. The operators were instructed to open the guards, mount a drill chuck into the spindle, close the guards and then reopen them to remove the chuck. Each complete cycle of these actions counted as one repetition out of ten. As shown in Table 4, the new guard was 10% faster than the old guard. The reduced improvement compared to the vice test is attributed to the added safety measure of the interlocked drawbar cover, illustrated in Figure 33. Despite this additional feature, which requires lifting and tilting to access the drawbar for tightening the tool into the spindle, the overall timing still shows an improvement.



Figure 33 - Interlocked draw bar cover

The third test involved adjusting the guard height to accommodate taller workpieces. Again, this test began in the same manner as the vice test, with the guards closed and set to their shortest position. The operators were instructed to adjust the guards to their maximum height and then return them to the shortest setting, with each complete cycle counting as one repetition out of ten. Table 4 shows that the new guard was 19% faster than the old guard. This improvement is attributed to the old guard requiring the adjustment of ten nuts, whereas the new guard only needs four grub screws for adjustment.

The fourth and final efficiency test was the cleanup test, simulating the clean-down that operators must perform between jobs and at the end of shifts. This test used five identical blocks of aluminium for each operator, clamped in the vice with a face mill cutter mounted in the spindle. The machine was cleaned, and then four 1mm depth cuts were made in each direction of table movement. The operators were then timed on cleaning the machine back to its original standard. This test was only conducted once to prevent unnecessary material waste and tool wear. Table 4 shows that the new guard also outperformed the old guard in this test, with a 12% improvement. This advantage is due to the new guard being mounted on an articulating arm attached to the side of the machine, whereas the old guard is table-mounted in the T-slots, making the cleaning of swarf and coolant more time-consuming.

Table 4 - Guarding systems efficiency test results

Guarding systems efficiency test								
Guard Type	Test	Time (s)						Improvement
		Operator 1	Operator 2	Operator 3	Operator 4	Operator 5	Average	
Old	Part Loading	307	298	295	304	295	299.8	49%
New		150	157	156	150	145	151.6	
Old	Tool Change	660	658	651	661	656	657.2	10%
New		598	590	596	593	591	593.6	
Old	Guard Adjust	1080	1086	1090	1081	1080	1083.4	19%
New		880	871	873	887	881	878.4	
Old	Cleandown	154	150	156	144	150	150.8	12%
New		129	134	132	134	136	133	

To summarise the efficiency testing, the new guarding system outperformed the old guarding system in every test, with an average time improvement of 20%. Although the milling machine is primarily used for development work, this time saving will provide Renishaw with cost savings through reduced labour time. To estimate the saved labour time, the average times of the tests were added, and the time difference between the new guard and the old

guard was calculated. Since these test tasks are expected to be carried out daily, this provides an estimate of the minimum cost saving. Equation 1 shows that the cost saving over one year is estimated to be over £16,000.

Combined average time for old guard = 2191.2 seconds

Combined average time for new guard = 1756.6 seconds

Time difference = 2191.2 – 1756.6 = 434.6 seconds

Time difference in hour = 434.6 ÷ 3600 = 0.12

Equation 1 - Labour cost saving

Applying labour rate of £79.95

Hourly saving = 0.12 × £79.95 = £9.65

Operators work a 37hr week for 47 weeks a year

Annual labour saving = (£9.65 × 37) × 47 = £16,781.35

5.4 Operator Feedback and Observations

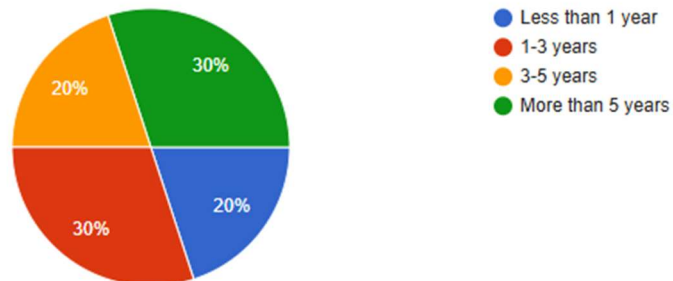
To complement the quantitative findings from the testing phase, qualitative data was collected through a structured user survey. The purpose of the survey was to evaluate operator perceptions of the newly implemented safety features, including their usability, effectiveness, and impact on workflow. The survey was administered to select staff at Renishaw Miskin site who have had experience using vertical milling machines, see Figure 34. It was explained to the operators which safety features had been added, and they were instructed to complete the survey following their use of the modified vertical milling machine. The participants involved Renishaw staff that are currently and no longer work on vertical milling machines, as well as apprentices who are currently undergoing training on vertical milling machines as part of their apprenticeship. This diversity helps ensure that the feedback is not limited to a single user profile, making the results more generic across different user groups.

Section A: General Information

What is your level of experience with vertical milling machines?

 Copy chart

10 responses



How frequently do you operate vertical milling machines?

 Copy chart

10 responses

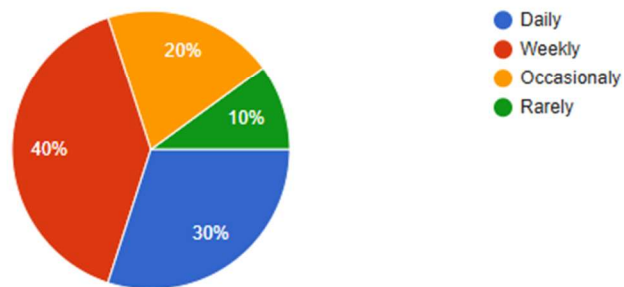


Figure 34 - Survey section A, Questions 1 & 2

The questionnaire was carefully designed to avoid leading questions and minimise bias in line with established best practices in survey methodology. According to Roopa and Rani (2012), effective questionnaire design requires clarity, neutrality in wording, and alignment with the research objectives to ensure that responses accurately reflect the views of participants. To this end, the survey employed a combination of Likert-scale items and open-ended questions, allowing for both quantitative analysis and the collection of nuanced qualitative insights. Questions were phrased in a neutral and non-suggestive manner to avoid influencing respondents' answers, a principle supported by Kurzahls (2021), who emphasises the importance of unbiased question framing in quantitative research.

The survey assessed several key areas, including operator confidence in machine safety, ease of use of the interlocked guards, accessibility and intuitiveness of the kick emergency

stop, and the perceived impact of the modifications on task efficiency. Respondents were also invited to provide suggestions for further improvements.

The results indicated a marked increase in operator confidence following the installation of the safety features. As illustrated in Figure 35 majority of respondents selected ratings of 4 or 5 on the Likert scale, where 5 represented 'strongly agree' and 1 represented 'strongly disagree'. This distribution suggests a strong positive reception of the implemented modifications. The high frequency of favourable responses reflects not only the perceived effectiveness of the safety features but also their successful integration into the existing workflow without causing disruption.

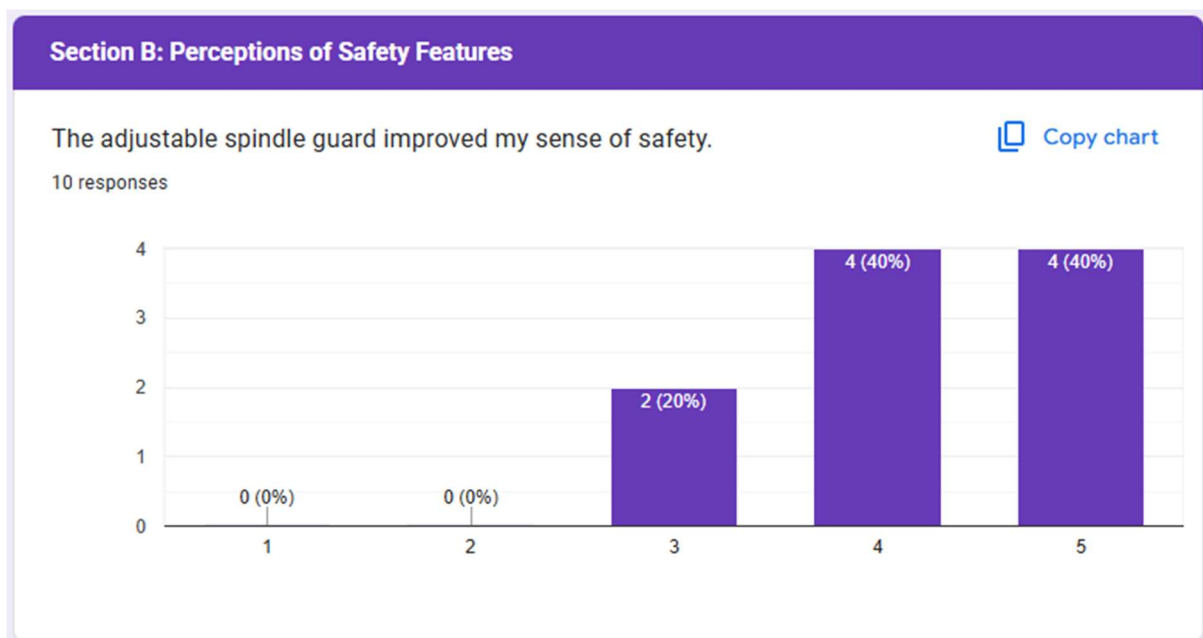


Figure 35 - Survey section B, Question 1

Most participants agreed that the interlocked guards provided both a physical and psychological barrier to hazardous areas, thereby enhancing their overall sense of safety during machine operation. The kick emergency stop (e-stop) was particularly well received, as illustrated in Figure 36, with respondents highlighting its accessibility and ease of activation. This positive feedback is likely attributable to the hands-on nature of vertical milling machine operation, where users often have both hands engaged. In such scenarios, the ability to activate an emergency stop using the foot offers a critical advantage, enabling a rapid response without requiring the operator to disengage from the task at hand.

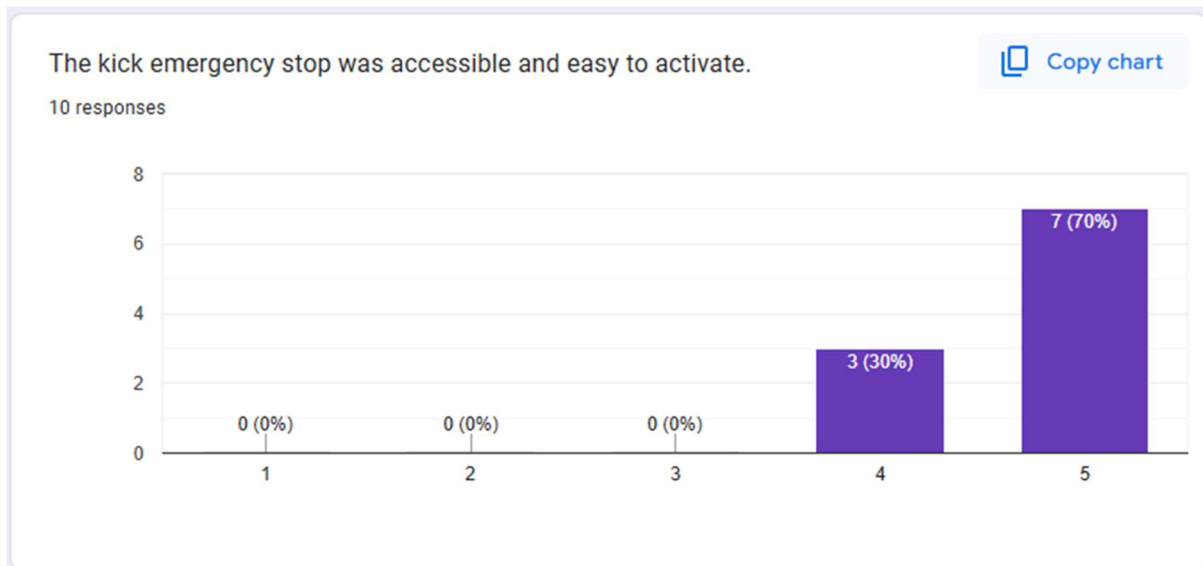


Figure 36 - Survey section B, Question 4

Furthermore, many respondents reported that the modifications did not hinder their workflow and, in some cases, contributed to smoother task execution due to the intuitive design of the safety mechanisms.

Open-ended responses provided additional insights, with a few operators recommending the inclusion of visual or audible indicators to further enhance safety awareness, as shown in Figure 37. Overall, the feedback supported the conclusion that the implemented modifications were effective and well-integrated, contributing positively to both safety and usability.

Do you feel the safety features could be improved in any way? Please provide suggestions.

10 responses

None
Make the spindle guard removable
Add an audible alert when interlock is triggered
Make the guard more adjustable
Add a visual system to show when interlocks are activated
Improve the visibility of guarding
no
Add light indicator
No

Figure 37 - Survey section C, Question 3

5.5 Limitations

While the methodology was designed to be robust and practical, several limitations must be acknowledged. Firstly, the testing was conducted on a single machine model, which may limit the generalisability of the results to other machine types or configurations. Secondly, the sample size for operator testing and feedback was relatively small, comprising a limited number of experienced users within a controlled workshop environment. This may not fully capture the range of user experiences in more diverse or industrial settings.

Additionally, long-term durability, maintenance requirements and corrosion resistance were not assessed due to time constraints. Future studies could address these limitations by incorporating a broader range of machine types, a larger and more diverse user base, and extended testing periods to evaluate wear and reliability over time.

6 Results and Discussion

The impact and rigidity tests were conducted to evaluate the structural integrity of the new guard system compared to the old guard system. Each guard was subjected to ten impacts using a 250-gram pendulum released from a horizontal position. The displacement resulting from the impact was measured using a digital plunger indicator. The new guard had a mean displacement of 15.04 mm, with a maximum displacement of 15.4 mm, while the old guard had a mean displacement of 16.64 mm, with a maximum displacement of 17.4 mm. These results indicate that the new guard system offers superior structural integrity with less displacement under identical conditions. This is attributed to the geometry of the new guard which positions the point of impact closer to the hinge, thereby reducing the resulting torque and displacement. The observed difference in movement is likely due to the increased resistance torque at the hinge, which limits the displacement during impact. This relationship between torque, force, and distance from the pivot is well-established in mechanical engineering and is supported by studies on hinge mechanics and rotational stiffness (Wang et al., 2023). Even if the new guard were to be subjected to a larger impact force from the operator, the guard would still follow the path of the operator's limb, preventing them from directly accessing the spindle. In contrast, the old-style hinges on the ends of the bed would cause the guard to pivot away from the spindle under increased force, creating a path for direct access.

The new guard system incorporates small grub screws for fine adjustment of the guard height. While this provides flexibility, it introduces potential reliability concerns due to the limited thread engagement and susceptibility to overtightening. Research by Eccles (2005) indicates that the coefficient of friction doubles by the tenth re-tightening of a threaded fastener, leading to decreased clamping force for a given torque. This suggests that the grub screws may not maintain their holding strength over time, potentially compromising the guard's ability to remain in its intended position under mechanical stress or vibration.

Four tests were conducted to measure the efficiency of the new guarding system compared to the old system. The new guard was 49% faster in part loading, attributed to its single-door design. It was 10% faster in tool changes, despite the additional interlocked drawbar cover. In guard height adjustment, the new guard was 19% faster, requiring adjustment of only four grub screws compared to ten nuts for the old guard. During cleanup, the new guard was 12% faster due to its articulating arm design. Overall, the new guarding system

demonstrated an average time improvement of 20%, translating to an estimated annual labour cost saving of over £16,000. This significant improvement in efficiency can be directly attributed to the design of the new guard which simplifies and accelerates everyday operational tasks.

A structured user survey indicated increased operator confidence and satisfaction with the new safety features. The interlocked guards and kick emergency stop were well-received, enhancing physical and psychological safety. The modifications were integrated smoothly into the workflow with suggestions for further improvements including visual or audible indicators. The high frequency of favourable responses reflects the perceived effectiveness of the safety features and their successful integration into the existing workflow without causing disruption. The kick emergency stop, in particular, was highlighted for its accessibility and ease of activation which is crucial in scenarios where operators have both hands engaged.

7 Cost-Benefit Analysis

Implementing the new guard system on the vertical milling machine involved a total project cost of £3,418. This investment aimed to enhance operator safety and improve efficiency during machine operation. The results from the efficiency testing demonstrated a significant improvement in operational speed, with the new guard system showing an average time improvement of 20% across various tasks. This increase in efficiency translates to an estimated annual labour cost saving of £16,780. This figure was achieved assuming the machine is operated 37 hours a week, for 47 weeks a year as shown in Equation 1. The streamlined design of the new guard, which simplifies and accelerates common operational tasks, is likely the primary factor contributing to these savings.

$$\text{Initial Cost} = £3418$$

$$\text{Monthly Saving} = £1398$$

Equation 2 - Project ROI (Return on Investment)

$$\text{Annual Saving} = £1398 \times 12 = £16780$$

$$ROI = \frac{(\text{£16,780} - \text{£3,418})}{\text{£3,418}} \times 100 = 390\%$$

The net benefit of the project can be calculated by considering the annual cost savings minus the initial project cost. For the first year, the net benefit is £13,362, see Figure 38. In subsequent years, the annual net benefit remains at £16,780 due to the continued efficiency improvements. The return on investment for the first year is approximately 390%, see Equation 2. The breakeven point is at 2.44 months, meaning returns would be seen in around 11 weeks, highlighting the project's high cost-effectiveness and substantial financial benefits.

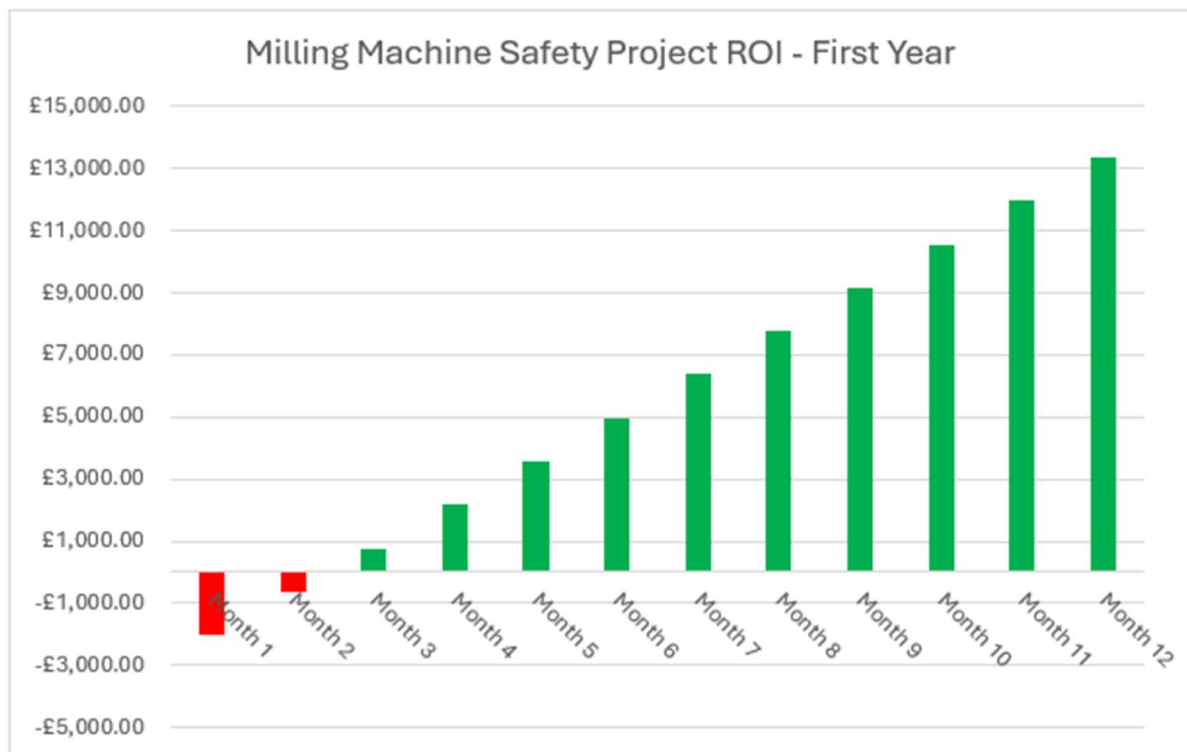


Figure 38 – Project 1 Year ROI (Return on Investment)

In addition to the immediate cost savings, the new guard system offers substantial long-term benefits. One of the most significant advantages is the increased safety against potential liability costs in the event of an injury. The HSE imposes fines for workplace injuries, with the average fine for machining-related incidents being approximately £250,000, see Figure 5. While it is not guaranteed that an injury would occur or that a fine would be imposed, the new guard system significantly reduces the risk of such incidents, thereby providing financial protection for Renishaw. This potential cost avoidance is a critical factor in the overall cost-benefit analysis.

8 Conclusion

This project set out to evaluate and implement an improved safety system for vertical milling machines within Renishaw's Custom Workshop, addressing the entanglement risks posed by rotating tooling. Through a systematic process involving risk identification, literature review and application of engineering decision-making tools such as FMEA and MCDA, the project successfully selected and installed an adjustable interlocked guarding system.

Initial concepts involving big picture ideas such as multiple sensors and camera systems were thoroughly evaluated during the early stages of the project but were ultimately not pursued further. This decision was not a reflection of their ineffectiveness in general, as these technologies are widely used in industrial safety applications. Instead, their exclusion was based on their unsuitability for the specific operating conditions and constraints of the vertical milling machine environment. Factors such as interference from coolant, swarf accumulation, limited line of sight, and integration complexity made these solutions impractical within the scope and timeframe of this project. As such, their elimination was a strategic decision to focus resources on systems that offered greater reliability, ease of implementation, and compatibility with existing infrastructure.

The final solution was chosen based on its strong performance in both risk assessment and multi-criteria analysis, and it was further supported by practical considerations including supplier support and installation feasibility. The new guard system was tested in accordance with ISO 14120, demonstrating improved mechanical resilience and usability over the previous system. Operator efficiency increased by an average of 20%, leading to a projected annual labour cost saving of over £16,000. As a bonus, user feedback also indicated a significant improvement in perceived safety and workflow integration.

From a financial standpoint, the project achieved a return on investment within just 11 weeks, further validating the effectiveness of the selected solution. While some advanced safety features such as pressure mats and signal towers were not implemented due to budget and time constraints, the foundation has been established for future integration.

To support the evaluation of project progress, a Gantt chart was maintained throughout and updated to reflect real-world deviations and milestone completions. The final Gantt chart, shown in Figure 39, illustrates the timeline of activities from initial planning through to procurement, installation and testing, providing clear evidence of structured project management and timely delivery.

Evaluating and Implementing Improved Safety Systems in Vertical Milling Machines

Emyr Hunnam

Renishaw PLC

Project Start Date: 03/10/2024

Scrolling Increment: 1

Legend:

On track

Low risk

Med risk

High risk

Not Started

Milestone description	Category	Assigned to	Progress	Start	Days
Proposal Submission	Milestone	EH	100%	04/10/2024	1
Supervisor meeting	On Track	EH, KL & KR	100%	01/11/2024	1
Contents page	Low Risk	EH	100%	05/11/2024	3
Research current guarding systems and sensor technologies	High Risk	EH	100%	08/11/2024	7
Process flow, understanding the process	Med Risk	EH	100%	15/11/2024	7
Project Aims & Objectives	High Risk	EH	100%	22/11/2024	6
Literature Review	High Risk	EH	100%	28/11/2024	10
Complete Literature Review	Goal	EH	100%	04/12/2024	1
Prepare Presentation	Med Risk	EH	100%	05/12/2024	5
Interim Viva	Milestone	EH	100%	11/12/2024	1
Respond to Viva Feedback	Low Risk	EH	100%	13/12/2024	14
Evaluation and final idea	High Risk	EH	100%	05/01/2025	30
Purchasing	High Risk	RB	100%	17/02/2025	28
Supplier initial date	High Risk	EH	100%	14/04/2025	1
Supplier actual installation date	High Risk	EH	100%	24/03/2025	1
Testing and safety analysis	High Risk	MD	100%	14/04/2025	5
Results and discussion	Med Risk	EH	100%	21/04/2025	2
Cost-Benefit analysis	Med Risk	EH	100%	23/04/2025	7
Write a project conclusion	Med Risk	EH	100%	25/04/2025	7
References and Appendices	Med Risk	EH	100%	02/05/2025	7
Final checks	Low Risk	EH	100%	09/05/2025	7
Report Submission	Milestone	EH	0%	19/05/2025	1
Create Final Presentation	High Risk	EH	0%	30/05/2025	14
Create Poster	High Risk	EH	0%	13/06/2025	14
Final Oral Exam	Milestone	EH	0%	27/06/2025	1

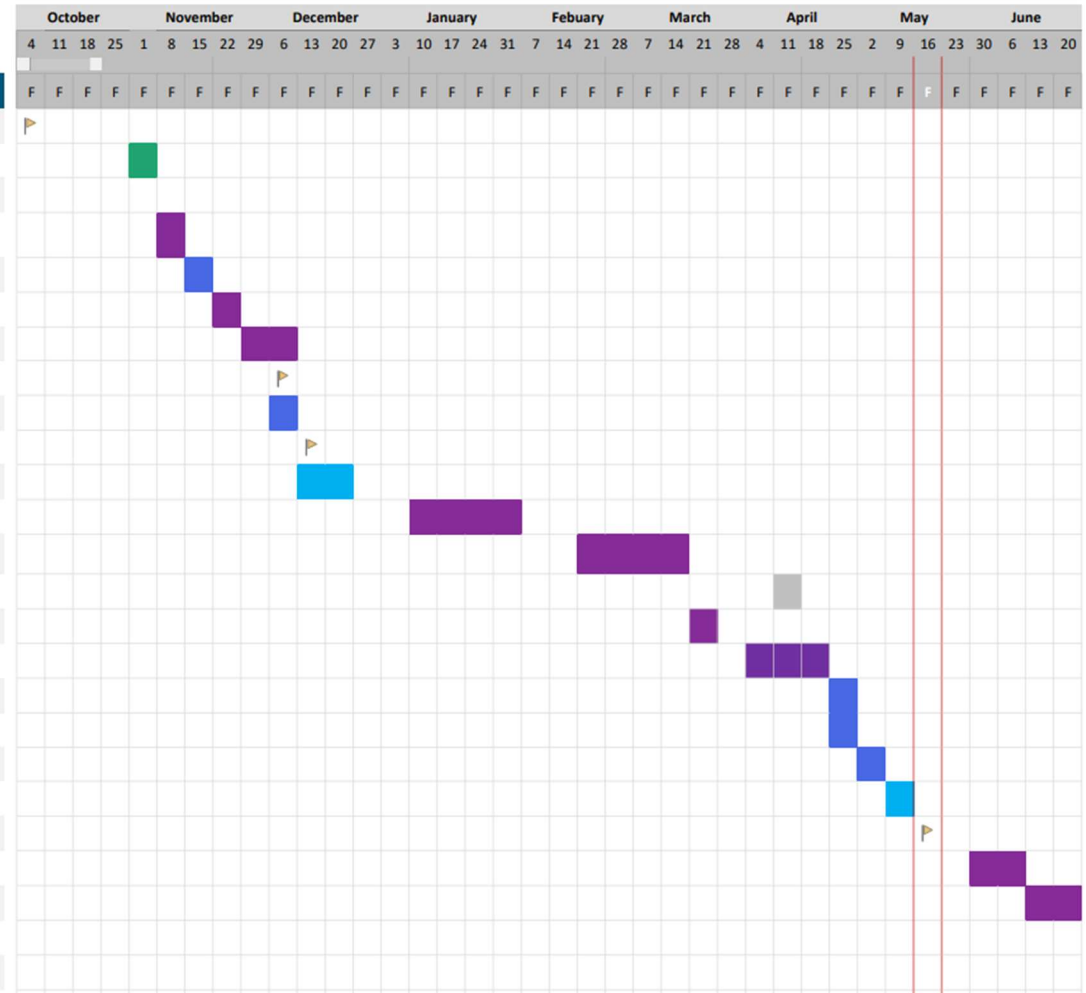


Figure 39 - Final Gantt Chart

In conclusion, the project not only enhanced operator safety but also demonstrated a replicable and cost-effective approach to safety system implementation in industrial manual machining environments. The methods used and results obtained provide valuable insights for future improvements and broader applications across the manufacturing sector.

9 Recommendations for future work

9.1 Gaps in research

The current research lacks data specific to manual machining, with most data referring to machining, predominantly focusing on CNC machining. This gap is significant because manual machining processes can differ substantially from CNC machining in terms of operational dynamics, human involvement, and safety requirements. Manual machining often involves more direct human interaction with the machinery, which can introduce unique risks and challenges that are not present in automated CNC processes. Future research should aim to collect and analyse data specific to manual machining to develop targeted safety measures and operational guidelines that address these unique aspects.

9.2 Gaps in validation methodology

To enhance the testing and validation of the guard, a larger sample size could be utilised. This could include staff from other Renishaw sites and even other companies to provide a more comprehensive evaluation. A larger and more diverse sample would help ensure that the findings are generic across different settings and user groups. Additionally, incorporating feedback from a broader range of users can uncover potential issues and areas for improvement that may not be evident in a smaller, more homogeneous sample.

Another methodological improvement would involve the use of more rigorous and varied testing protocols. For instance, incorporating real-world usage scenarios and stress tests can provide a more accurate assessment of the guard's performance under typical operating conditions. This could include simulating different types of machining operations, varying the duration and intensity of use, and testing the guard's response to unexpected events or failures. By adopting a more comprehensive and realistic testing approach, future studies can better evaluate the guard's effectiveness and identify any potential weaknesses or areas for enhancement.

9.3 Gaps in testing

Due to time constraints, two potentially valuable physical tests were not conducted as part of this evaluation. These were fatigue testing and thermal/chemical resistance testing.

Fatigue or cycle testing is essential for assessing the long-term reliability of moving components such as hinges, sliders, or adjustable mechanisms. This test typically involves subjecting the guard to thousands of open-close cycles to simulate extended use. Over time, such testing can reveal issues like wear, loosening, or misalignment that may not be apparent in short-term evaluations. However, the duration and equipment required to perform a meaningful number of cycles (e.g., 10,000 or more) exceeded the available timeframe for this project.

Thermal and chemical resistance testing evaluates how well the guard materials withstand exposure to elevated temperatures and industrial substances such as coolants, lubricants, or cleaning agents. These conditions are common in machining environments and can degrade materials, affect transparency, or compromise mechanical integrity. Conducting this test would require controlled environmental conditions and extended exposure periods, which were not feasible within the scope of this study.

Whilst these tests were not performed, their absence represents a limitation in fully assessing the long-term functional safety and environmental durability of the guard systems. Future work should include these evaluations to provide a more comprehensive understanding of guard performance under real-world operating conditions.

9.4 Time Constraints

Due to time constraints, pressure mats were not implemented during the course of this project. Despite this, they scored highly in both the Failure Modes and Effects Analysis (FMEA) and Multi-Criteria Decision Analysis (MCDA), highlighting their potential value as a safety enhancement. Advice from Renishaw's facilities team indicated that pressure mats must be installed prior to the guarding system, which was not feasible within the available project timeline. However, future integration of pressure mats could significantly enhance operator safety by providing an additional layer of control.

Pressure mats can be configured as either normally open or normally closed, depending on their intended safety function. According to E-Switch, Inc. (2023), normally open switches do not conduct electricity until activated, whereas normally closed switches conduct electricity until the circuit is interrupted. This flexibility allows pressure mats to serve both permissive and protective roles. For example, a mat positioned at the front of the machine within the operator's designated work zone could be configured as normally open, ensuring that the machine cannot start unless the operator is present. Conversely, mats located around the sides and rear of the machine—areas deemed as danger zones—could be configured as

normally closed, such that any entry into these regions would immediately trigger a machine stop.

This dual-configuration approach would improve safety without compromising operator comfort or workflow efficiency. It enables intelligent zoning of the workspace, ensuring both proactive and reactive safety responses based on operator position. See Figure 40 for a conceptual layout of pressure mat placement.

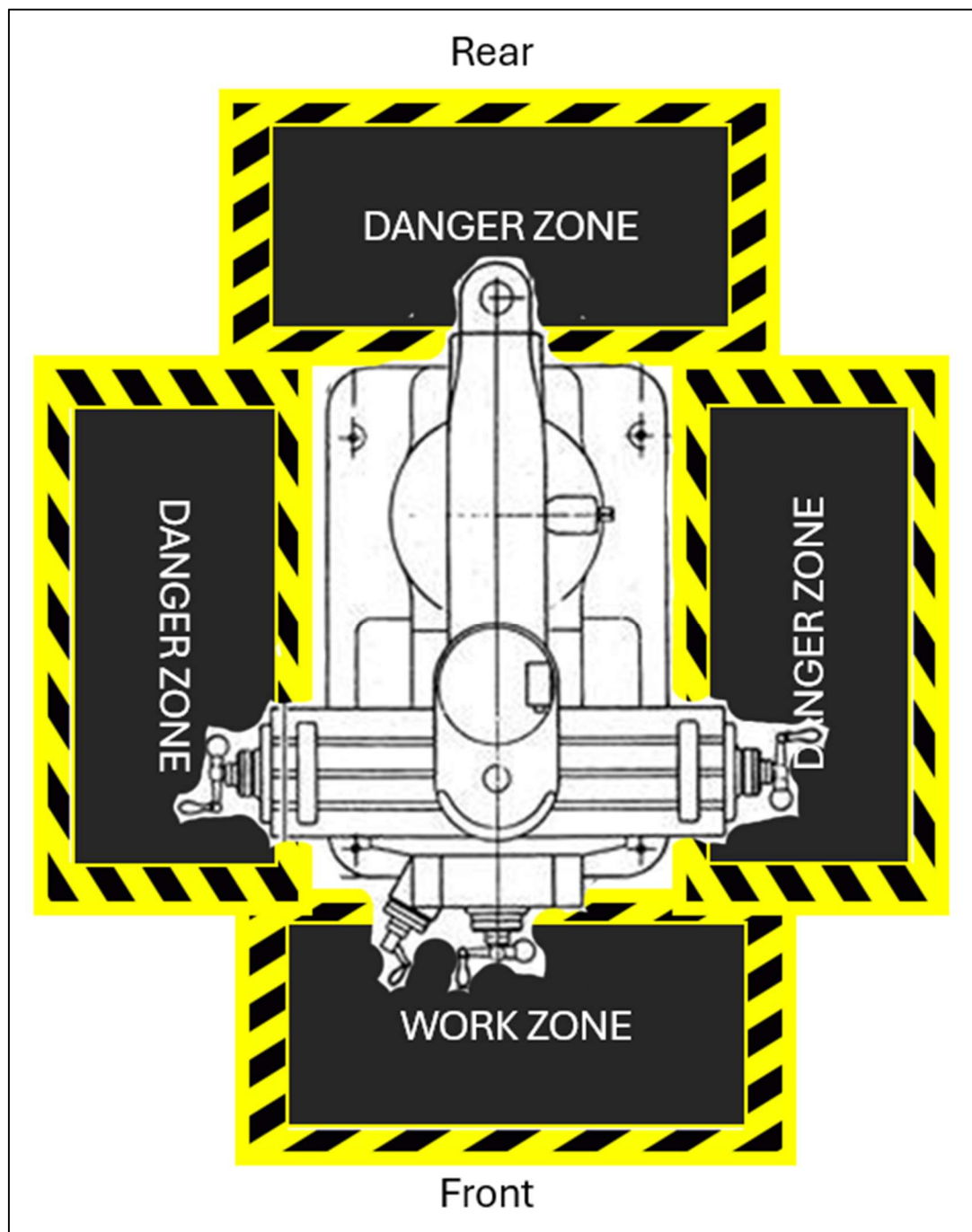


Figure 40 - Pressure mat configuration

9.5 Future work

To complement both the current guarding system and the pressure mat configuration, visual and audible alert systems could also be integrated to enhance operator awareness and safety. These suggestions came via the operator feedback survey and were not part of the initial ideas. Light towers, which originate from the Japanese concept of *Andon*, are a form of visual management used to communicate the operational status of machinery (Lean Enterprise Institute, 2025). These towers typically display three colours: red, amber, and green, as illustrated in Figure 41. According to Tarlengco (2023), the red light indicates a critical issue such as halted production, amber signifies a warning or a condition requiring attention, and green represents normal, issue-free operation.

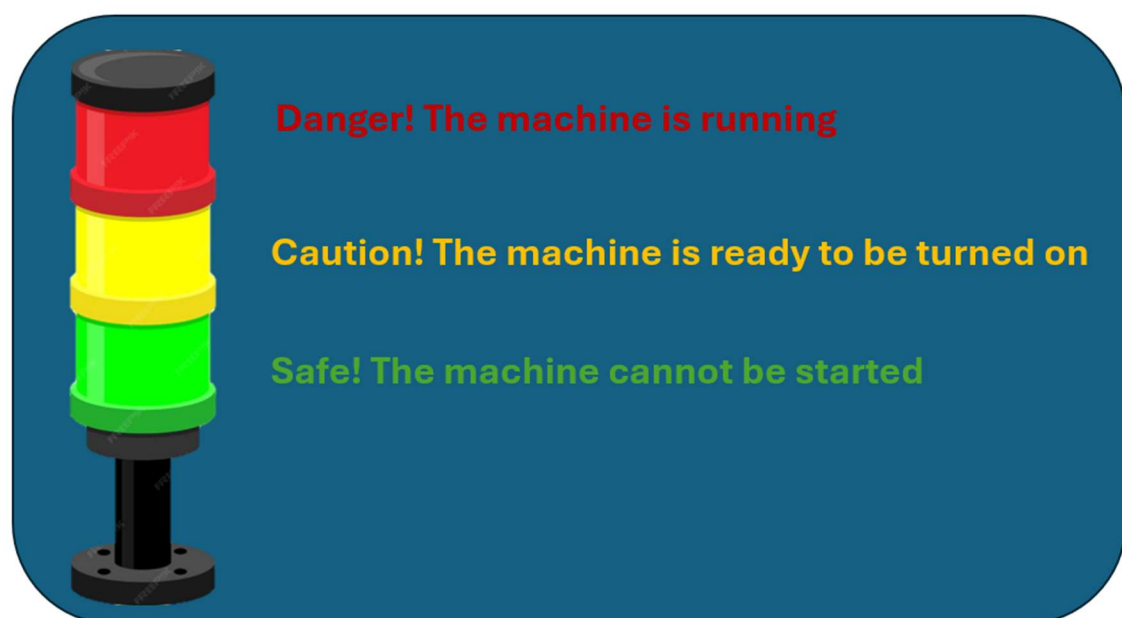


Figure 41 - Andon Light Tower (Korosi, 2025)

In the context of a vertical milling machine, these visual cues could be adapted to show different safety states. A green light could indicate that the machine is in a safe condition, for example when the guard doors are open and the spindle cannot be started. An amber light could indicate that the machine is in a ready state, such as when the guard doors are closed and the emergency stops are disengaged. A red light would signal active danger, such as when the spindle is rotating.

To further enhance operator safety, audible systems such as alarms could also be included. These alarms could alert both the operator and others nearby to a potential hazard. For

example, if a pressure mat detects that the operator has stepped away from the machine while the spindle remains active, an alarm could sound to discourage unattended operation and make surrounding personnel aware of the risk. This multi-sensory approach would strengthen the overall safety system by providing immediate and clear warnings based on machine state and operator behaviour. The proposed future solution incorporating these features is illustrated in Figure 42.

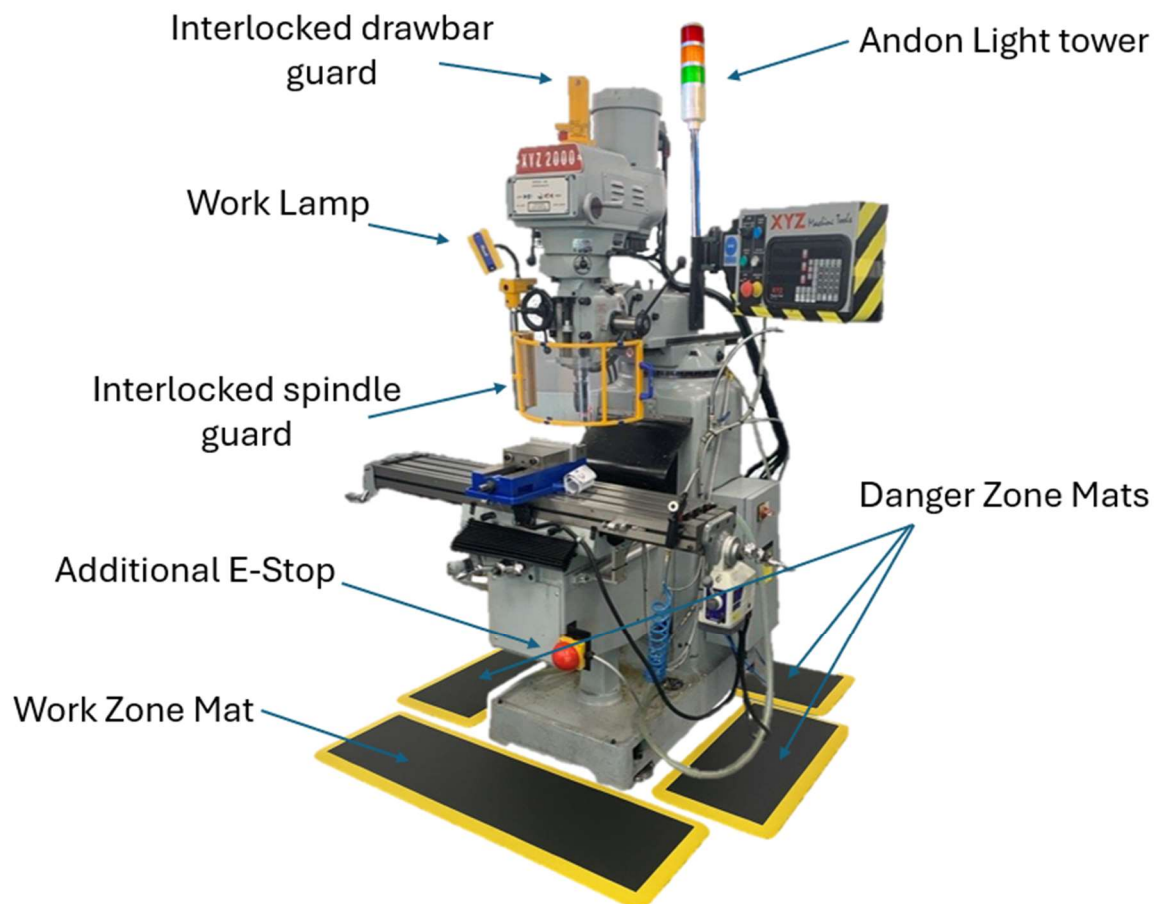


Figure 42 - Proposed future work

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11 Appendices

11.1 Accident Rate Data

Year	Number of fatal Injuries to employees	Number of non-fatal Injuries to employees
1974	257	336,722
1975	202	327,757
1976	181	323,465
1977	179	326,785
1978	159	328,001
1979	149	299,209
1980	130	253,266
1981	123	12,316
1982	137	12,286
1983	118	12,453
1984	142	12,494
1985	124	13,175
1986	109	179,706
1987	99	179,909
1988	94	183,063
1989	108	185,640
1990	88	180,707
1991	64	170,103
1992	53	158,085
1993	59	151,633
1994	46	156,390
1995	42	147,150
1996	53	155,250
1997	54	163,976
1998	63	160,663
1999	38	164,033
2000	46	161,629
2001	42	157,666
2002	41	156,297
2003	22	161,706
2004	40	152,230
2005	36	147,959
2006	34	143,197
2007	28	138,253
2008	29	133,155
2009	22	122,695
2010	25	116,686

2011	27	111,299
2012	20	79,166
2013	10	77,546
2014	15	75,919
2015	26	72,029
2016	16	69,912
2017	12	70,452
2018	25	69,306
2019	12	65,543
2020	18	51,229
2021	17	62,481
2022	15	61,406
2023	13	61,663

11.2 Survey Questions

Operator Feedback Survey - Vertical
Milling Machine Safety Enhancements

Please answer the following questions. This should only take 5 minutes. Thank you for participating.

Section A: General Information

1. What is your level of experience with vertical milling machines?

Mark only one oval.

- ☐ Less than 1 year
☐ 1-3 years
☐ 3-5 years
☐ More than 5 years

2. How frequently do you operate vertical milling machines?

Mark only one oval.

- ☐ Daily
☐ Weekly
☐ Occasionally
☐ Rarely

Section B: Perceptions of Safety Features

3. The adjustable spindle guard improved my sense of safety.

Mark only one oval.

	1	2	3	4	5	
Stro	☐	☐	☐	☐	☐	Strongly Agree

4. The drawbar guard was easy to use and did not interfere with my tasks.

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

5. The interlock mechanisms functioned reliably during use.

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

6. The kick emergency stop was accessible and easy to activate.

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

7. The safety features did not negatively affect my workflow.

Mark only one oval.

1 2 3 4 5

Stro ☐ ☐ ☐ ☐ ☐ Strongly Agree

8. I would feel confident using this machine in a production environment.

Mark only one oval.

	1	2	3	4	5	
Strongly Disagree	☐	☐	☐	☐	☐	Strongly Agree

Section C: Usability and Workflow Impact

9. Did the safety features make any tasks easier or more difficult? Please explain.

10. Were there any situations where the safety features interfered with your work? If yes, please describe.

11. Do you feel the safety features could be improved in any way? Please provide suggestions.

Section D: Overall Impressions

12. What did you find most useful or effective about the new safety features?

13. Do you have any additional comments or feedback?

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