



Design of a Semi-Automatic Charging System for Tumbler Shot Blasting Machines in the Metal Foundry Industry

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ABSTRACT

The transport and distribution of flanged housing products to the fettling and shotblast tumbler zones in the metal casting industry heavily relies on manual material handling, which involves strenuous physical loads and highly repetitive motions. These conditions pose a significant risk of musculoskeletal disorders (MSDs) for operators and hinder overall production cycle efficiency. This study aims to design and develop a semi-automatic charging system as an automated material feeding solution to optimize distribution workflows and enhance ergonomic standards at the workstation. Structural analysis confirms that the entire mechanical framework, including the main chassis and lifting arms, demonstrates exceptional structural integrity and is fully secure under maximum operational loads. The actual bending stress sustained by the structure remains well below the allowable stress threshold of the specified structural steel. Furthermore, critical powertrain elements and supporting transmission components—specifically the shafts and rotary bearings—are verified to have adequate safety factors and dynamic service-life estimates for long-term production cycles. From an occupational safety perspective, implementing a panel-controlled automated system significantly improves working postures, as assessed by the Rapid Upper Limb Assessment (RULA) framework. This systemic transition completely eradicates static loads and awkward postures, thereby fostering a substantially safer, more ergonomic, and highly efficient working environment for foundry operators.

Contribution to Sustainable Development Goals (SDGs):

SDG 8: Decent Work and Economic Growth

SDG 9: Industry, Innovation, and Infrastructure

SDG 12: Responsible Consumption and Production

1. INTRODUCTION

1.1. Research Background

The metal casting industry in Indonesia is currently facing severe competition from international market players, particularly from India and Pakistan. Metal casting fundamentally involves pouring molten metal into a mold to solidify into a specific component before undergoing further processing [1]. This manufacturing process consists of critical stages, ranging from mold preparation, pouring, and cooling, to surface finishing. Among these, the

finishing stage plays a vital role in refining geometric shapes, achieving dimensional accuracy, and enhancing surface characteristics to meet functional and aesthetic requirements [2]. Generally, surface finishing improves material properties such as corrosion resistance and wear behavior. In the casting industry, the finishing line comprises fettling, shot blasting, machining, and painting. Shotblasting serves as a critical bridge between rough fettling and high-precision operations by establishing initial surface cleanliness and roughness [3].

In tumbler shotblast machines designed for batch processing of small-to-medium castings, abrasive steel shots are propelled at



high velocities to remove molding sand, scale, and impurities while enhancing coating adhesion [4]. However, field observations in the studied foundry revealed that the Work-In-Process (WIP) material handling for charging loads into the tumbler shotblast machine remains entirely manual. This process requires two operators to repeatedly load casting products weighing 5-10 kg per unit, with a total batch capacity of up to 350 kg. Over an 8-hour shift, this repetitive manual handling creates severe fatigue, extending charging load times by 15–20 minutes per batch. In accordance with Lean Manufacturing principles, utilizing double labor for non-value-added, repetitive tasks represents a major form of waste [5], causing significant operational delays and material bottlenecks.

Furthermore, manual material handling poses severe Occupational Safety and Health (OSH) risks. Operators manually lift a cumulative load of approximately 2.1 tons per day in awkward, bent postures. Such excessive physical exertion is a primary cause of physical fatigue and Musculoskeletal Disorders (MSDs), particularly lower back injuries [6]. These operational inefficiencies and ergonomic hazards will worsen as the company plans to install a new 1-ton melting furnace, which will dramatically increase casting volume at the finishing line.

To address these challenges, this study proposes a semi-automatic charging load machine for tumbler shotblast units. The system is engineered to safely, efficiently, and ergonomically hold and feed WIP materials into the machine chamber. The ergonomic improvement is validated using the Rapid Upper Limb Assessment (RULA) method to systematically measure upper-limb postural risks [7]. Ultimately, this solution aims to reduce labor requirements from two operators to one supervisor, streamline cycle times, eliminate bottlenecks, and mitigate occupational injury risks to support the foundry's planned production expansion.

1.2. Literature Review

1.2.1. Surface Finishing and Shotblasting Process in Metal Casting

Surface finishing serves as a critical bridge between raw casting and high-precision downstream processes, dictating the dimensional accuracy, geometric integrity, and surface characteristics necessary for functional application [8]. Among various finishing techniques, shotblasting is recognized as a vital mechanical surface preparation method. By propelling abrasive steel shots at high velocities, it effectively eliminates molding sand, scale, and impurities while establishing an optimal surface roughness profile for subsequent operations. In batch-processing operations utilizing tumbler shotblast machines, maintaining consistent pre-processing surface preparation (fettling) and stable loading mechanisms is essential to prevent degradation of surface quality and production bottlenecks [9].

1.2.2. Lean Manufacturing and Manual Material Handling (MMH)

In competitive manufacturing environments, eliminating non-value-added activities—or waste (*muda*)—is fundamental to operational efficiency. Lean Manufacturing principles emphasize the minimization of idle time, material accumulation, and redundant labor usage. Manual Material Handling (MMH), particularly repetitive lifting and manual loading of heavy Work-In-Process (WIP) materials, introduces severe operational

variability. Studies show that physical operator fatigue directly causes inconsistencies in loading durations, leading to extended non-value-added time, severe material queuing, and machine idle time during production cycles [10].

1.2.3. Occupational Ergonomics and Risk Assessment via RULA

Repetitive manual lifting of heavy loads poses severe Occupational Safety and Health (OSH) risks, highly correlated with physical fatigue and Musculoskeletal Disorders (MSDs), particularly in the lower back region. To mitigate ergonomic hazards in manual manufacturing tasks, quantitative assessment tools such as the Rapid Upper Limb Assessment (RULA) are extensively utilized. RULA provides a systematic evaluation of postural stress on upper-body segments—including the neck, trunk, and upper limbs—delivering action-level scores that guide necessary engineering controls and mechanical interventions [11].

1.3. Research Objective

The primary objective of this study is to evaluate the technical feasibility and safety of a newly designed semi-automatic charging load mechanism for a tumbler shotblast machine. Specifically, this research aims to analyze the ergonomic risk levels associated with operator working postures using the Rapid Upper Limb Assessment (RULA) method, while simultaneously assessing the structural integrity of the machine frame through Finite Element Analysis (FEA) to ensure mechanical safety based on Von Mises stress criteria and the allowable Factor of Safety (FoS)..

2. MATERIALS AND METHODS

2.1. Design Drawings

Figure 1 below is a design drawing of Semi-Automatic Shot Blast Tumblers

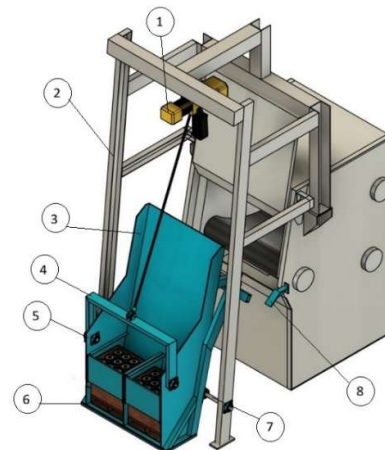


Figure 1. Design Sketch of a Semi-Automatic Shot Blast Tumbler

Description:

- | | |
|------------------------|--------------------|
| 1. PolipastoH | 5. Bearing UCF |
| 2. ShotBlast Tumbler | 6. Main Frame |
| 3. Bucket Material Box | 7. Shaft |
| 4. Holder Swing Bucket | 8. Stopper Machine |

2.2. Data Collection and Management

The data collection and management phase serves as the foundation for determining the technical parameters in the machine design process. To ensure the design results are mechanically and ergonomically valid, the collected data is categorized into two main groups:

2.2.1. Primary Data

Primary data was obtained through direct field observations and measurements at the shotblast tumbler workstation within the metal casting industry to capture actual operational conditions:

a. Operational Load Capacity: Identifying that the total material load of Work-in-Process (WIP) reaches up to 350 kg per batch, with individual product weights varying between 5 and 10 kg.

b. Physical Workload: Documenting that an operator lifts a cumulative total load of approximately 2.1 tons per workday, which serves as the baseline data for the risk analysis using the Rapid Upper Limb Assessment (RULA) framework.

c. Cycle Time: Documenting the machine's cleaning duration, which ranges between 10 and 30 minutes, and the manual charging time, which requires an additional 10 to 15 minutes.

d. Resource Allocation: Observing the utilisation of two operators for a single machine unit, which will be targeted for efficiency optimisation down to a single supervisory operator.

2.2.2. Data Management and Transformation

The gathered raw data was subsequently processed and transformed into specific design parameters through the following stages:

a. Design Parameter Analysis: Converting the mass data of 350 kg into a loading force (N) to calculate the required torque and motor power.

b. 3D Modeling: Translating the geometry data of the shotblast machine chamber into Autodesk Fusion 360 software to determine the optimal dimensions of the bucket and structural frame.

c. Charging Integration: Utilizing the weight variability data of the WIP materials to establish engineering specifications capable of maintaining automated material distribution accuracy.

2.3. Structural Frame Strength Analysis

A structural frame strength analysis was performed to guarantee that the chassis and bucket can withstand static operational loads. The finite element method (FEM) was utilized to simulate the loading conditions on critical sections of both the frame and the bucket. The primary analyzed parameter includes the Von Mises stress. The structure is declared compliant if the maximum sustained stress remains below the yield strength of the selected material. [12]and[13].

2.4. Ergonomic Analysis

An ergonomic analysis was conducted to ensure that the machine design effectively mitigates the risks of fatigue and occupational injuries, despite the system operating automatically. The primary objectives of this analysis include eliminating manual material handling (MMH) activities for work-in-process (WIP) materials weighing approximately 5–15 kg, reducing the requirement for

two operators who previously performed repetitive manual charging every 15–50 minutes, and establishing a safe loading zone height for both forklift operators and personnel working around the equipment. The machine design is declared compliant if the Rapid Upper Limb Assessment (RULA) grand score satisfies the condition ≤ 2 , with the specific criteria defined as follows:

a. Elimination of Manual Handling: Eradicating manual material handling processes by operators for WIP products weighing between 5 and 15 kg.

b. Safe Loading Zone Height: Ensuring the material loading area height complies with safety standards for both forklift operations and manual interventions.

c. Accessibility and Postural Safety: Providing ease of access for operational and maintenance processes without forcing technicians into awkward postures.

Ultimately, these measures aim to cultivate a safe working environment and minimize the risk of Musculoskeletal Disorders (MSDs)[14].

3. RESULT AND DISCUSSION

3.1. Existing Conditions of the Charging Process

The production workflow within the finishing line initiates with the fettling process to separate the Work-in-Process (WIP) components from the gating system. These products are subsequently arranged in wooden crates and transported to the shotblast tumbler zone by forklift. Field observations indicate significant material accumulation or bottlenecks at this stage, resulting from a charging system that still relies heavily on Manual Material Handling (MMH). Despite simultaneously employing two operators, the manual charging process fails to match the material arrival rate of the preceding operation, thereby disrupting the overall efficiency of the production flow.

Technically, the manual charging process for each crate takes about 10 to 15 minutes. In comparison, the shotblast tumbler machine operates on a cycle time ranging from 15 to 30 minutes per batch, with a maximum load capacity of 350 kg. The tactical mismatch between the manual charging duration and the machine's operational cycle creates a pronounced inefficiency, leaving the equipment frequently idle while awaiting material readiness. This condition results in substantial waste of human resources and operational time, directly diminishing the overall productivity of the finishing line.



Figure 2. Shot Blast Tumblers Machine



Figure 3. Manual Materials Handling

Manual Material Handling (MMH) during the charging process simultaneously employs two operators to repetitively lift Work-in-Process (WIP) components weighing 3–15 kg to fulfill a 350-kg batch capacity. This high-frequency lifting is exacerbated by transferring materials over a ± 3 -meter distance from the queue area to the machine chamber. Over an 8-hour shift, this constant repetition imposes severe biomechanical loads on the lumbar spine and upper extremities. This highly inefficient workflow causes extreme physical fatigue, consistently triggers chronic fatigue and Musculoskeletal Disorders (MSDs) due to poor working postures. [15]

3.2. Structural Strength Analysis of the Frame

This technical focus was executed comprehensively to ensure that the design meets mechanical safety standards and is operationally viable. As the foundation of this analysis, calculating the elevation angle parameters and stroke length is an essential preliminary step. The geometric data generated from these computations will be utilized as the primary baseline to evaluate the overall structural integrity, while concurrently serving as the governing parameters for selecting the appropriate bucket frame specifications. [16] and [17]

The visual representation of the charging system modeling at the maximum lifting angle is illustrated in detail in Figure 4.

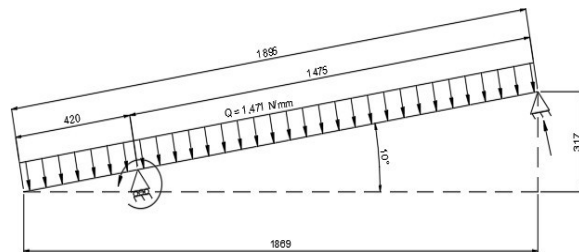


Figure 4. Maximum Structural Diagram

The position of the load arrow in the figure represents the gravitational weight force ($F = 2,830.38 \text{ N}$), which originally acts downward. Therefore, the value of the uniformly distributed load perpendicular to the surface is calculated by dividing the force using the following formula:

$$Q = (F \times \cos 10) \div 1,895 \quad (1)$$

$$= (2,830.38 \text{ N} \times 0.9848) \div 1,895$$

$$= 1,471 \text{ N/mm}$$

Since no external force acts parallel to the longitudinal axis of the member, the horizontal reaction force at the pinned support B is zero.

$$\sum F_x = 0 \text{ or } \sum H = 0 \quad (2)$$

A counter-clockwise rotation is defined as positive (+). The uniformly distributed load, q , is represented as a concentrated load acting precisely at the midpoint of the arm span ($1,895/2 = 947.5 \text{ mm}$), thereby inducing a counter-clockwise bending moment about point B. Conversely, the reaction force R_A exerts an upward force, causing a clockwise rotation (-) about point B:

$$\sum M_B = 0$$

$$+(Q \times L \times 947.5) - (R_A \times LAB) = 0$$

$$2,641,198.89 - 14,575 \times R_A = 0$$

$$R_A = \frac{2,641,198.89}{1,475}$$

$$R = 1,790.64 \text{ N}$$

The upward force (support reaction) must equal the downward force (uniformly distributed load):

$$\sum F_y = 0 \quad (3)$$

$$R_A + R_B - (Q \times L) = 0$$

$$1,790.64 + R_B - (1,471 \times 1,895) = 0$$

$$1,790.64 + R_B - 2,787.55 = 0$$

$$R_B = 2,787.55 - 1,790.64$$

$$R_B = 996.91 \text{ N}$$

Shear Force (V) and Bending Moment (M) Equations

Because the structural member design includes an overhang (a suspended load extending 420 mm beyond the support), the internal force equations are divided into two cutting intervals:

Interval 1: Left Boundary Segment ($0 < x < 420 \text{ mm}$)

In this interval, only the uniformly distributed load acts from above.

$$\text{Normal Force: } N(x) = 0$$

$$\text{Shear Force: } V(x) = -1,471 \cdot x$$

$$\text{Bending Moment: } M(x) = -0.5 \cdot 1,471 \cdot x^2$$

Interval 2: Inter-Support Segment ($420 < x < 1,895 \text{ mm}$)

The cross-sectional cut is made after passing support A; hence, the reaction force R_A is included in the calculation.

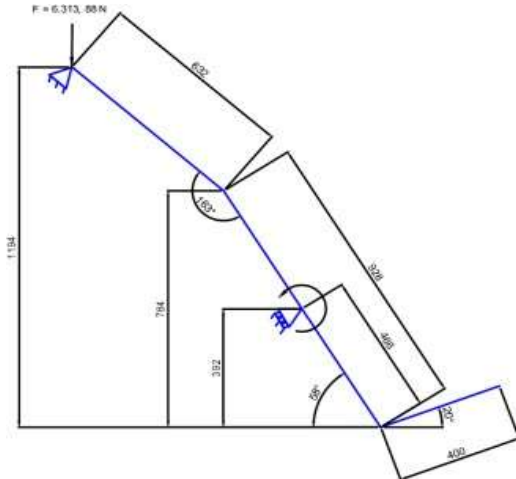
$$\text{Normal Force: } N(z) = 0$$

$$\text{Shear Force: } V(x) = -1,471 \cdot x + 1,790.64$$

$$\text{Bending Moment: } M(x) = -0.5 \cdot 1,471 \cdot x^2 + 1,790.64 \cdot (x - 420)$$

Determination of the Maximum Bending Moment Point

The bending moment reaches its absolute maximum value when the first derivative of the moment equation (or the shear



force value) equals zero, as shown in the following equation:

Figure 5. Maximum Structural Diagram of the Machine Frame

$$\frac{d(M(x))}{dx} = 0 \quad (4)$$

$$1,790.64 - 1,471 \times x = 0$$

$$1,471 \times x = 1,790.64$$

$$x = 1,217.29 \text{ mm}$$

The maximum bending moment value is calculated by substituting the distance x into the moment equation for Interval 2:

$$M_{max} = -0.5 \times 1,471 \times (1,217.29)^2$$

$$+ 1,790.64 \times (1,217.29 - 420)$$

$$M_{max} = 337,803.9 \text{ N} \cdot \text{mm}$$

After obtaining the maximum bending moment value of $337,803.9 \text{ N} \cdot \text{mm}$, the section modulus parameter (Z) can be calculated to determine the steel profile material specification that remains secure against the allowable bending stress [18], utilizing the following equation:

$$Z_x = \frac{M_{max}}{\sigma_{allowable}} \quad (5)$$

$$Z_x = \frac{337,803.9}{125}$$

$$Z_x = 2,702.43 \text{ mm}^3$$

Referring to the obtained Z_x value of $2,702.43 \text{ mm}^3$, a UNP $80 \times 40 \times 5$ steel channel profile was selected for the material specification, as it is deemed to satisfy the mechanical criteria and align with the design specifications.

3.3. Structural Strength Analysis of the Machine Frame

The subsequent phase focuses on the structural analysis of the machine's supporting frame. This framework serves as the primary support that will withstand the total load of the products

and material crates weighing 288.52 kg , while concurrently supporting the bucket mass of 355.1 kg . In the computation process, the entire load is assumed to act statically as a concentrated load located at the upper section of the structure, expressed in the following equations:

$$F_m = M_{material} \times g \quad (6)$$

$$F_m = 288.52 \times 9.81$$

$$F_m = 2,830.38 \text{ N}$$

$$F_b = w_b \times g$$

$$F_b = 355.1 \times 9.81$$

$$F_b = 3,483.5 \text{ N}$$

Therefore, the total loading force (F_T) exerting pressure on the upper end of the frame structure is:

$$F_T = F_m + F_b \quad (7)$$

$$F_T = 2,830.38 \text{ N} + 3,483.5 \text{ N}$$

$$F_T = 6,313.88 \text{ N}$$

The visual representation of the charging system modeling at the maximum lifting angle is illustrated in detail in Figure 5 below:

The position of the load arrow in the figure represents the gravitational weight force ($F = 2,830.38 \text{ N}$), which originally acts downward. Therefore, the value of the uniformly distributed load perpendicular to the surface is calculated by dividing the force using the following formula [19]:

Horizontal Distance of the Upper Segment Arm (L_{x1}):

$$L_{x1} = 632 \times \cos(40.45^\circ)$$

$$L_{x1} = 632 \times 0.7609$$

$$L_{x1} = 480.96 \text{ mm}$$

Horizontal Distance of the Upper Segment Arm (L_{x2}):

$$L_{x2} = 462 \times \cos(58^\circ)$$

$$L_{x2} = 462 \times 0.5299$$

$$L_{x2} = 244.82 \text{ mm}$$

Total Horizontal Distance of the Upper Segment Arm

$$L_x = L_{x1} + L_{x2}$$

$$L_x = 480.96 + 244.82$$

$$L_x = 725.78 \text{ mm}$$

Regarding the support reactions at the pivot point acting parallel to the longitudinal axis of the member, the reaction forces at the support are expressed as follows:

$$\sum F_x = 0 \quad \text{or} \quad \sum H = 0$$

$$H_{pivot} = 0 \text{ N}$$

Subsequently, the computations are performed as follows:

$$\sum F_y = 0 \quad \text{or} \quad \sum V = 0$$

$$V_{pivot} - 6,313.88 = 0$$

$$V_{pivot} = 6,313.88 \text{ N}$$

$$\Sigma M_{pivot} = 0$$

$$6,313.88 \times (480.96 + 244.82) - M_{pivot} = 0$$

$$M_{pivot} = 4,582,489.6 \text{ N} \cdot \text{mm}$$

After determining the sustained reaction forces, the internal forces are calculated using the following equations. Due to the structural angular change, the calculation is divided into two intervals [20]:

Interval 1: Upper Arm ($0 < x < 632 \text{ mm}$)

$$\text{Normal Force: } N(x) = -6,313.88 \times \sin(40.45^\circ) = -4,096.32 \text{ N}$$

$$\text{Shear Force: } V(x) = -6,313.88 \times \cos(40.45^\circ) = -4,804.78 \text{ N}$$

Interval 2: Upper Arm ($0 < x < 462 \text{ mm}$)

$$\text{Normal Force: } N(x) = -6,313.88 \times \sin(58^\circ) = -5,354.50 \text{ N}$$

$$\text{Shear Force: } V(x) = -6,313.88 \times \cos(58^\circ) = -3,345.85 \text{ N}$$

$$\text{Bending Moment: } M(x) = 3,036,620.9 - 3,345.85 \times x$$

3.4. Structural Strength Analysis of the Charging Load Machine

The material applied to construct the supporting framework in this design is ASTM A36 standard steel channel profiles. The specific mechanical properties and characteristics of this material are detailed in Table 1 below. ASTM A36 was selected primarily for its high weldability, structural versatility, widespread availability, and cost-effectiveness in heavy-duty industrial framing. Although foundry environments are exposed to abrasive sandblast dust, ASTM A36 provides sufficient structural integrity and mechanical durability when paired with protective surface coatings (e.g., anti-corrosion epoxy primers), making it a more practical choice than higher-grade alloys.

Table 1. Material Specifications

Parameter	Description
Material	Astm A36
Modulus Elastisitas (E)	200.00 Mpa (N/mm ³)
Density	7,85 G/cm ³
Yield Strength	250 Mpa
Ultimate Tensile Strength	400-550 Mpa
Modulus Of Elasticity	200 Gpa
Bulk Modulus	140 Gpa
Poisson's Ratio	0,260
Shear Modulus	79,0 Gpa

This simulation was performed to analyze the force distribution and determine the maximum stress points susceptible to occurring within the critical zones of the frame structure. To ensure the design's safety level, the stress results from the simulation must be strictly verified to remain below the allowable operational stress. The mathematical formulation utilized to calculate the allowable stress of the frame is presented in the following equation:

$$\sigma_{allowable} = \frac{\sigma_y}{sf \times k} \quad (8)$$

$$\sigma_{allowable} = \frac{250}{2 \times 1}$$

$$\sigma_{allowable} = 125 \text{ MPa}$$

Setting Constraints and Loads

The computational focus of this study encompasses the dimensional determination and structural strength analysis of the arm component and the unit.

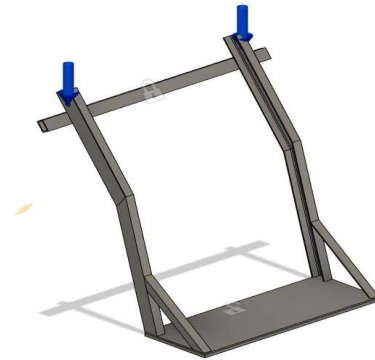


Figure 6. Setting Constraints and Loads



Figure 7. Von Misses Stress

Figure 7. illustrates the structural response and stress distribution of the charging system framework obtained from the Finite Element Analysis (FEA). The simulation focuses on evaluating the Von Mises stress generated under the specified maximum operational loads. As visualized by the color contour scale, the overall structure exhibits excellent mechanical integrity, dominated by low-stress zones highlighted in blue.

Quantitative analysis reveals that the critical area experiencing the maximum concentration of stress is located at the joints of the upper cross-member beam, yielding a peak Von Mises stress (σ_{max}) of 60.413 MPa at coordinates ($x: -389.768, y: 1,612.401, z: 1,115.055$). Conversely, the minimum stress recorded within the structure drops to 3.046×10^{-5} MPa. Based on the predetermined engineering criteria, the maximum sustained stress (60.413 MPa) remains significantly below the allowable stress threshold ($\sigma_{allowable} = 125 \text{ MPa}$) and well under the yield strength of the ASTM A36 structural steel ($\sigma_y = 250 \text{ MPa}$). Therefore, the simulated structural configuration is verified to be mechanically safe, robust, and

completely secure against structural failure under static loading conditions.

Safety Factor

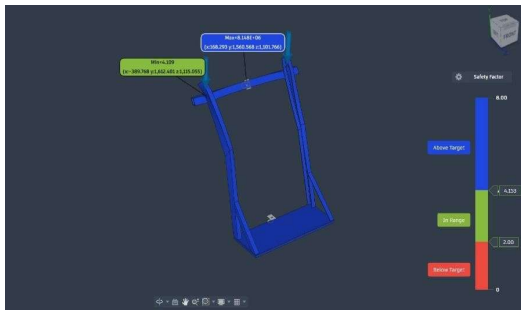


Figure 8. Safety Factor

Figure 8. displays the Safety Factor distribution map across the charging system framework derived from the Finite Element Analysis (FEA). This simulation serves to validate the structural reliability and safety margins under maximum operational loading conditions. Visually, the framework is overwhelmingly dominated by the blue contour zone, indicating that the structural capacity remains well within the "Above Target" safety criteria.

Quantitative assessment shows that the minimum safety factor (SF_{min}) recorded on the structure is 4.109, located precisely at the upper cross-member joint coordinates ($x: -389.768, y: 1,612.401, z: 1,115.055$). Conversely, the maximum safety factor reaches an optimal peak value of 8.148×10^6 at coordinates ($x: 168.293, y: 1,560.568, z: 1,101.766$). Given that the minimum safety factor (4.109) significantly exceeds both the critical failure threshold ($SF = 1.0$) and the predetermined engineering design target ($SF \geq 2.0$), the framework is structurally verified to possess excellent reserve strength. The results confirm that the proposed mechanical configuration is highly reliable and structurally sound for long-term manufacturing operations.

3.5. Ergonomic Analysis Using RULA

The following presents the results of the occupational posture identification and ergonomic analysis utilizing the Rapid Upper Limb Assessment (RULA) framework. This evaluation process was simulated using CATIA software, employing a 3D digital human mannequin representing the anthropometric data of the Japanese worker population. The Japanese mannequin database was selected because the default CATIA software library lacks a specific Indonesian anthropometric standard. Among the available regional mannequin databases, the Japanese population data was chosen as the most suitable reference due to the close physical and anthropometric similarities between Asian populations. Through this simulation, the spatial placement configuration of the control buttons on the shotblast machine's structural frame was visually evaluated. The outcomes of this component positioning represent the operator's interactive posture and actual working method, as illustrated in the figure below:

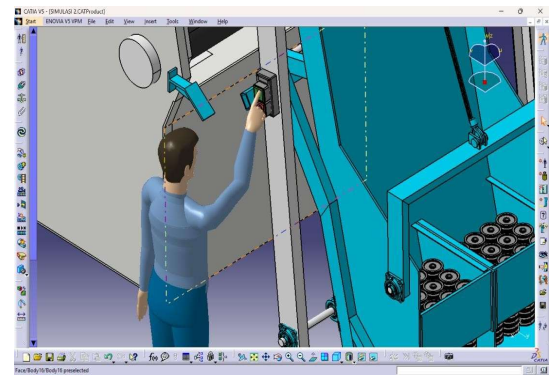


Figure 9. Ergonomic Work Methods

Furthermore, the placement configuration of the buttons on the shotblast machine frame results in calculated postures and working methods with an evaluation score satisfying the condition $RULA \leq 2$. Although the software displays contour areas in yellow, the evaluation results remain well within the acceptable tolerance range; thus, the design is declared Safe and viable for operation. While a RULA score of 2 indicates a low ergonomic risk that is acceptable for immediate implementation, long-term health and operational efficiency can be further optimized. For future improvements, introducing a height-adjustable control panel mechanism (e.g., an adjustable mounting bracket) is recommended. This enhancement would accommodate wider anthropometric variations among operators, prevent cumulative fatigue during prolonged static posture, and support long-term musculoskeletal wellness in daily foundry operations.

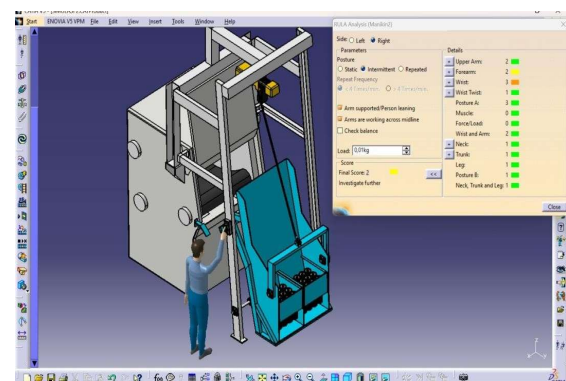


Figure 10. Ergonomic Work Methods

4. CONCLUSION

This study successfully engineered a semi-automated charging system to optimise the material-handling workflow for shot-blast tumblers in the metal casting industry. The structural frame strength analysis, validated via Finite Element Method (FEM) simulations using an ASTM A36 steel UNP $80 \times 40 \times 5$ profile, confirmed excellent mechanical integrity. The maximum sustained Von Mises stress reached 60.413 MPa, which is significantly below the allowable stress threshold of 125 MPa and yield strength of 250 MPa. Concurrently, the minimum safety factor was determined to be 4.109, heavily exceeding the critical design target of $SF \geq 2.0$. Furthermore, the ergonomic evaluation simulated via CATIA demonstrated that the strategic

spatial placement of the control panel effectively minimized awkward operator postures, achieving a RULA grand score of ≤ 2 . Consequently, the proposed design is verified to be mechanically robust, safe, and highly viable for eliminating manual lifting risks while boosting manufacturing efficiency.

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