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# DISEÑO DE UN SISTEMA MECATRÓNICO DE LIMPIEZA DE BARRILES TIPO A PARA LA CERVECERÍA ARTESANAL LA PAZ

Trabajo de titulación previo a la obtención del título de Ingeniero en Mecatrónica

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***David Clavijo***

Quiero dedicar este trabajo de titulación con mucho esfuerzo a mis padres, Diego y Sandra, por su sacrificio, apoyo constante y amor incondicional a lo largo de todos estos años. Esto es una meta más y una promesa cumplida hacia ustedes y desde la distancia les dedico todo esto con mucho amor. Son ellos mi mayor inspiración para alcanzar esta meta. Este logro es tanto mío como de ellos.

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# Índice

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# DISEÑO DE UN SISTEMA MECATRÓNICO DE LIMPIEZA DE BARRILES TIPO A PARA LA CERVECERÍA ARTESANAL LA PAZ

# DESIGN OF A MECHATRONIC SYSTEM FOR CLEANING OF TYPE A BARRELS FOR LA PAZ CRAFT BREWERY

David Gilberto Clavijo Marthell [1], , Edy Leonardo Ayala Cruz [2],

## Resumen

Este artículo presenta el diseño de un sistema mecatrónico automatizado para barriles Tipo A, desarrollado específicamente para la Cervecería Artesanal La Paz, ubicada en Cuenca, Ecuador. Esta investigación propone una solución técnica que responde a la necesidad de mejorar los procesos de higienización de los barriles utilizados en la producción cervecera, garantizando condiciones óptimas de salubridad, reduciendo tiempos operativos y disminuyendo la intervención manual.
El sistema está diseñado para satisfacer las necesidades reales del proceso de producción artesanal, caracterizado por limitaciones de espacio, presupuesto y acceso a soluciones tecnológicas industriales. El proyecto integra componentes mecánicos, neumáticos y electrónicos controlados por un PLC Siemens S7-1200 y monitoreados a través de una interfaz HMI, organizados bajo una arquitectura funcional que permite la limpieza interna y externa del barril. La estructura está fabricada en acero inoxidable AISI 304, con un mecanismo de sujeción neumático adaptable a múltiples tamaños de barriles.
El diseño se valida mediante modelado 3D, simulación estructural por elementos finitos y modelado del flujo del proceso mediante un diagrama de tuberías e instrumentación (P&ID), que proporciona una visualización clara del flujo del proceso de limpieza desde la entrada hasta la descarga del fluido.
Los resultados muestran mejoras significativas en la eficiencia, la higiene y la repetibilidad del proceso, lo que posiciona al sistema como una alternativa técnica adaptable, económica y eficaz para la producción de cerveza artesanal.

La principal contribución de este trabajo es ofrecer una solución económica y adaptable a los requisitos técnicos de una cervecería artesanal.

***Palabras clave***: Limpieza de barriles, Cervecería Artesanal, Automatización Industrial, Sistema Mecatrónico.

## Abstract

This article presents the design of an automated mechatronic system for Type A kegs, developed specifically for the La Paz Craft Brewery, located in Cuenca, Ecuador. This research proposes a technical solution that addresses the need to improve the sanitation processes for kegs used in beer production, ensuring optimal sanitation conditions, reducing operating times, and minimizing manual intervention.
The system is designed to meet the real needs of the craft production process, characterized by limited space, budget, and access to industrial technological solutions. The project integrates mechanical, pneumatic, and electronic components controlled by a Siemens S7-1200 PLC and monitored through an HMI interface, organized under a functional architecture that allows for internal and external cleaning of the keg. The structure is made of AISI 304 stainless steel, with a pneumatic clamping mechanism adaptable to multiple keg sizes.
The design is validated using 3D modeling, finite element structural simulation, and process flow modeling using a piping and instrumentation diagram (P&ID), which provides a clear visualization of the cleaning process flow from fluid inlet to fluid discharge.
The results show significant improvements in efficiency, hygiene, and process repeatability, positioning the system as an adaptable, cost-effective, and effective technical alternative for craft beer production.

The main contribution of this work is to offer an economical and adaptable solution to the technical requirements of a craft brewery.

***Keywords***: Keg Cleaning, Craft Brewery, Industrial Automation, Mechatronic System.

# 1. Introduction

## 1.1. Relationship Problem

The relationship to the problem has been divided into three fundamental aspects with distinct technical, economic, and social approaches.

Regarding the technical approach, the cleaning process for usable type A kegs represents a critical stage in the beer production cycle, as it directly influences the quality of the final product, the hygiene of the system, and the useful life of the components. In craft breweries like Cervecería La Paz, this procedure is mostly performed manually, which leads to variability in results, longer operating times, and exposure to human error. Furthermore, the lack of automation limits the precise control of variables such as pressure, flow rate, temperature, and exposure time to the cleaning agent, which compromises the standardization and traceability of the process. The absence of mechatronic solutions adapted to this environment hinders the implementation of efficient, safe, and repeatable processes.

From an economic perspective, implementing commercially available industrial cleaning systems often entails a high initial investment, as well as additional operating, maintenance, and training costs. For Cervecería La Paz, these systems are not viable due to their size, technical complexity, and lack of adaptability. The inefficiency of the manual method also generates excessive use of water, energy, and chemicals, increasing operating costs and affecting business profitability. In this sense, there is a need to develop economical, energy-efficient solutions tailored to the real dimensions of the artisanal process, without compromising their effectiveness.

In the social sphere, manual barrel cleaning involves repetitive physical effort that can lead to fatigue, strain injuries, or prolonged exposure to chemicals for operating personnel. This impacts occupational health, worker well-being, and the perception of professionalism within the workplace. Additionally, the lack of standardization in this process can lead to inconsistencies in product quality, affecting consumer confidence.

## 1.2. Project Justification

Keg cleaning is a critical process within the production cycle, as it ensures proper hygiene and prevents contamination of the final product. Reducing cleaning times to less than 8 minutes per keg allows for a higher volume of kegs processed per hour, which translates into an increase in production capacity without the need to expand infrastructure. By reducing cleaning time per keg, a more efficient use of resources such as water, energy and cleaning chemicals is achieved. This not only reduces operating costs, but also has a positive impact on the sustainability of La Paz Craft Brewery by minimizing resources and waste generation, as well as implying fewer interruptions in the production cycle and better overall plant efficiency. Shorter cleaning times allow for reduced costs related to labor, energy and machine wear, generating significant savings over time.

The project focuses on solving the problem of washing type A barrels at the La Paz Brewery, focusing on the need to speed up and optimize this process for barrels of various sizes and volumes. Currently, the brewery faces limitations due to the lack of a cleaning system capable of adapting to different barrel sizes, which increases the time spent on these tasks. Efficiency in cleaning type A barrels is essential to maintain high hygiene standards and ensure the quality of the final product. Currently, this efficiency is negatively affected due to the use of obsolete technology in the plant, which compromises the results of the cleaning and disinfection process.

The analysis of operational needs allowed the identification of key requirements for the design of the system, prioritizing functionality and safety. Existing technologies applied in similar processes were used as a reference, which allowed the creation of a system that combines mechanical and electronic components, including sensors, actuators and a PID controller for automation.

## 1.3. Objectives

### 1.3.1. General Objective

Design a mechatronic system for cleaning type A barrels for the La Paz Craft Brewery.

### 1.3.2. Specific Objectives

- Examine the existing cleaning and disinfection system for 10, 15, 20, 30, 40, and 50-liter Type A barrels to identify the variables involved.

- Design the mechanical system for the 10, 15, 20, 30, 40, and 50-liter Type A barrel cleaning system, incorporating an automatic washing process using a conveyor belt feed system and a cleaning and disinfection booth for at least one barrel at a time.

- Design the electrical, automation, and control system for the 10, 15, 20, 30, 40, and 50-liter Type A barrel cleaning system.

- Validate the design of the 10, 15, 20, 30, 40, and 50-liter Type A barrel cleaning system through analysis and simulation of the mechanical and automation system.

### 1.4. Methodology & Analysis of the State of the Art

This research is framed within a quantitative, applied and technological approach, whose purpose is to develop a practical solution to a specific problem of La Paz craft brewery: the efficient cleaning of type A barrels. An experimental engineering design methodology is used, which includes the analysis of requirements, mechatronic design, and the evaluation of its performance through controlled tests. This methodology allows validating the technical feasibility of the proposed system and its effectiveness in the real context of use.

The following are research questions:

What technical and sanitary parameters should be considered for the mechanical and automated design of a Type A keg cleaning system?

What type of mechatronic architecture is most suitable for integrating pneumatic components, sensors, actuators, and controllers into a compact and efficient system?

What control logic is most efficient for automating the cleaning cycle, considering pressure, timing, sequences, and operational safety?

How can the structural and functional strength of the system be validated using 3D modeling and finite element analysis without building a physical prototype?

The cleaning and sanitation of reusable kegs is a critical process in the production cycle of craft beer. Proper hygiene ensures product quality, prevents contamination, and guarantees compliance with health regulations. However, small- and medium-sized breweries often face difficulties implementing automated cleaning solutions due to high costs, space limitations, and lack of adaptable technologies. Failure to follow proper procedures can lead to microbiological contamination, flavor alterations, and product loss, which directly affects the brewery's reputation. For this reason, various cleaning systems have been developed over time with varying levels of automation, costs, and technical features. This section analyzes the state-of-the-art of these systems, with an emphasis on their applicability to the craft brewery context.

Manual systems are the simplest and most economical. They generally consist of hoses, brushes, and cleaning solutions applied directly by the operator. Although widely used in small breweries, they have significant limitations: high variability in results, high risk of cross-contamination, operator exposure to chemicals, and excessive water and energy consumption. Furthermore, internal keg cleaning is often inefficient due to the difficulty of accessing all internal surfaces evenly [1].

Semi-automatic systems represent a technological evolution compared to manual methods. These systems incorporate pumps, solenoid valves, flow, temperature, and pressure sensors, and in some cases, programmable logic controllers. Although they still require operator intervention for tasks such as coupling the keg or starting the cycle, they allow for more precise parameters, improve process repeatability, and reduce resource consumption. They are a viable option for craft breweries looking to increase efficiency without incurring the high costs of fully automated systems.

CIP (Clean In Place) systems are fully automated systems designed for large-scale industrial plants. These systems allow cleaning cycles to be performed without disassembling components or requiring manual intervention. They utilize multiple tanks for cleaning solutions, recirculation pumps, conductivity, temperature, and pressure sensors, and are controlled by advanced PLCs connected to HMI interfaces. These systems offer high efficiency, operational safety, resource savings, and compliance with international regulations, but their high cost and complexity make them difficult for small-scale artisanal producers [2].

Despite advances in cleaning systems, there is a technological gap between industrial solutions and the real needs of craft breweries. Most options available on the market are geared toward large producers and fail to consider the space, budget, and technical capacity limitations of smaller facilities. This context creates the need to develop semi-automated, compact, modular, low-cost, and easy-to-operate cleaning systems capable of ensuring reliable hygienic results without requiring a complex infrastructure.

Over the past two decades, several types of keg cleaning systems have been developed, ranging from basic manual setups to fully automated Clean-In-Place (CIP) systems. Manual systems are low-cost but lack repeatability and are prone to human error. Semi-automatic systems introduce basic automation—such as pumps and solenoid valves—but still require operator intervention. Fully automated systems, while efficient, are often inaccessible to small breweries due to high implementation costs.

**Table 1.** Cleaning System Comparison [3].

| Feature | Manual | Semi | Auto (CIP) |
|---|---|---|---|
| Degree of Automation | None | Partial | Complete |
| Implementation Cost | Low | Average | High |
| Process Repeatability | Low | Average | High |
| Technical Requirement | Low | Average | High |
| Efficiency in Resource use | Low | Average | High |
| Operational Security | Low | Average | High |
| Environment Adaptability | High | High | Low |
| Maintenance | Simple | Average | Specialized |
| Common Use | Small | Growing | Large scale |

**Note:** A comparative table is presented between the different types of cleaning systems.

Despite the availability of these systems, there is a clear technological gap for low-cost, compact, and modular solutions designed specifically for artisanal breweries. This presents an opportunity to apply mechatronic engineering principles to design systems that are not only efficient but also affordable and adaptable to varying barrel sizes and production volumes.

### 1.5. Brewery Background

La Paz Craft Brewery, also known as Latitud Cero, located in Cuenca, Ecuador, has distinguished itself in the local market for the quality and authenticity of its craft beers. This brewery, which uses selected raw materials and traditional fermentation techniques, distributes its products in type A barrels with capacities ranging from 10 to 50 liters. The constant reuse of these barrels makes the cleaning process a determining factor. One of the critical processes in this production is the cleaning of the barrels, both inside and out, to ensure the quality and purity of the beer, avoiding any contamination that could affect the flavor or safety of the product.

Currently, the brewery cleaning process is largely performed manually and with outdated technology, which has led to a number of operational challenges, including a lack of consistency in cleaning and the inability to completely eliminate organic and microbiological residues left in kegs after use. The use of outdated equipment and techniques impacts both production times and the efficiency of removing residues and contaminants. As a result, there is a latent risk of cross-contamination and altered beer flavor, which can negatively impact the final product quality. The lack of an automated system directly impacts cycle times, the amount of water and energy used, and the levels of sanitation achieved, compromising compliance with strict health regulations governing the brewing industry.

Furthermore, the manual process involves a high degree of human intervention, which increases the likelihood of errors. Variations in washing times and inconsistencies in the application of cleaning protocols can result in poorly sanitized kegs, with residues of yeast, bacteria, or other contaminants that compromise product safety. These problems impact the lifespan of the equipment, as poor cleaning can accelerate the wear of kegs and other components used in the plant.

The cleaning process for each keg takes an average of 8 minutes, requiring one person for the entire procedure, which is performed every 15 days. Considering the large number of kegs available, the method itself is time-consuming, resulting in significant lost time, which could be reused during downtime periods outside of business hours. At La Paz Craft Brewery, there is a high beer production rate, with production times of 5 and 8 hours, respectively. Due to this high production, a constant flow of 4 elements is required for the estimated production. Therefore, the plant has a cleaning system responsible for washing and disinfecting these elements. This system is called an automated cleaning system. This system requires manual implementation, is entirely dependent on its workers, and generates a significant loss of time between each cleaning cycle.

### 1.6. Problem

In beer production, ensuring quality standards is essential, which requires the implementation of cleaning protocols at all stages of the process. One of the key areas is the cleaning of beer barrels Kegs, which are used as containers for storing beer. With technological advances over time, the washing of barrels has progressed significantly, and today there are automatic machines dedicated to this task. Small and medium-sized craft beer producers in Ecuador have experienced notable growth in response to increased demand. However, these companies often resort to manual methods for cleaning barrels due to the high cost of automatic machinery. In the labor field, the Ministry of Labor has developed the Technical Standard for Safety and Occupational Health, which establishes technical guidelines for safety at work and the prevention of occupational risks in places and work centers, being mandatory for all employers in the country [4].

La Paz Craft Brewery, located in Cuenca, Ecuador, is distinguished by its commitment to the quality of its products and the adoption of sustainable practices in its operations. However, one of the most common challenges in the craft brewing industry is ensuring proper cleaning and disinfection of barrels. These elements are essential to prevent cross-contamination that can affect the quality of the beer and compromise the health of consumers. In addition, the lack of an automated system for this process can increase operating costs, cleaning time, and waste of resources, such as water and chemicals.

In artisanal breweries such as Cervecería La Paz, keg cleaning is still performed manually or semi-manually, resulting in long operation times, inconsistent cleaning results, and overuse of resources such as water, detergents, and energy. Additionally, operators are frequently exposed to physical strain and chemical risks, raising concerns about occupational safety.

During internal cleaning, one of the main problems is the accumulation of organic residues such as yeast, hops, proteins and fermented sugars, which can adhere to the walls of the keg and form biofilms that are difficult to remove. These biofilms can host unwanted microorganisms, such as bacteria and wild yeasts, which affect the quality of the next batch of beer and can generate microbiological contamination.

Another major challenge is the geometry of the keg, which makes it difficult to access all surfaces with conventional cleaning methods. The cylindrical shape and narrow neck of the keg limit the effectiveness of spray systems, which can generate incomplete zones.

Currently, the sanitation of kegs is carried out manually or semi-manually, representing a non-standardized procedure that depends heavily on the operator's skill and lacks rigorous technical control. This situation compromises process efficiency and product hygiene quality, as it fails to ensure consistent and thorough cleaning in each cycle.

From a technical perspective, the absence of automation prevents the repeatability of critical parameters such as pressure, washing time, temperature, increasing the risk of cross-contamination and affecting product consistency. Additionally, there is no reliable mechanism for securing and positioning the barrels during the process, leading to potential workplace accidents, damage to the containers, and resource loss.

From an operational and economic standpoint, the current process involves high consumption of water, detergents, and electricity, resulting in increased operational costs without a clear optimization strategy. Constant human intervention also decreases overall system productivity, limits the scalability of production, and affects the brewery's efficiency.

From a social perspective, there is a physical burden placed on the workers responsible for cleaning, as they must handle heavy barrels under conditions that may compromise their safety. The repetitive nature of manual tasks, exposure to chemicals, and contact with high temperatures pose risks to worker health and well being.

The present academic article, entitled "Design of a mechatronic system for cleaning of type A barrels for the La Paz Craft Brewery", aims to design an efficient system that guarantees thorough cleaning at all necessary stages, minimizing the risk of contamination and optimizing the resources used in the process and complying with current health regulations at an affordable cost for small and medium producers.

The design of the mechatronic system proposed in this research considers the future implementation of advanced technologies that allow precise and efficient control of the cleaning process. This system not only seeks to ensure uniform cleaning both inside and outside the barrels, but also to strictly adhere to applicable national and international health regulations and local food hygiene regulations.

## 2. Materials & Methods

This article presents the design of a mechatronic keg cleaning system tailored to the technical, economic, and spatial constraints of Craft Brewery La Paz. Unlike previous solutions, the proposed system:

- Integrates mechanical, pneumatic and electronic components for semi-automated cleaning process.
- Includes a pneumatic clamping system for safe and repeatable keg positioning.
- Is validated through structural modeling and process simulation.
- Is modular and cost-efficient, suitable for scaling in small breweries.

This research follows an experimental engineering design methodology with a technological and applied focus. The goal is to develop a functional and validated mechatronic solution to address the cleaning inefficiencies of Type A barrels in La Paz Craft Brewery. The methodology is structured in five main phases:

1. **Diagnosis of Current System**: A performance assessment was conducted using the KCPE (Keg Cleaning Process Efficiency) indicator, which evaluates time, hygiene level, and resource usage in the current cleaning process.

2. **Mechanical System Design**: A robust stainless-steel structure was designed to support and secure barrels of different volumes using pneumatic clamping mechanisms. Multiple structure proposals were compared using a weighted decision matrix.

3. **Automation and Control System Design**: A Siemens S7-1200 PLC was selected to implement the cleaning sequence, including valve control, sensor monitoring, and actuator operation. A Human-Machine Interface (HMI) was designed for real-time system interaction.

4. **Simulation and Validation**: Finite Element Analysis (FEA) was performed to evaluate structural integrity under operating loads. The control process was simulated through diagrams including P&ID and control logic schematics.

5. **Performance Comparison and Analysis**: The proposed system was compared with the current setup in terms of operation time, resource consumption, and hygienic effectiveness, demonstrating significant improvements.

### 2.1. Theoretical Framework

In Ecuador, national health and hygiene standards are established mainly in the Organic Law of Health, which regulates and controls the production, importation, distribution, storage, transportation, marketing, and sale of processed foods, medicines, and other products for human use and consumption, in order to guarantee their safety, security, and quality [5].

Furthermore, the National Agency for Sanitary Regulation, Control and Surveillance (ARCSA) in

Ecuador has issued technical sanitary regulations, such as ARCSA-DE-067-2015-GGG, which establishes the hygienic-sanitary conditions and requirements that the processes must meet in order to protect the health of the population and guarantee the supply of healthy and safe products [6]. The ARCSA mandates that food processing plants, including breweries, must comply with Good Manufacturing Practices (GMP) as per the regulations mentioned beforehand. The regulations do not detail specific procedures for cleaning kegs, but breweries are expected to implement cleaning and sanitation protocols that ensure the safety of the final product. This involves establishing standardized procedures for cleaning kegs, ensuring the removal of residues and proper disinfection to prevent contamination. Records of these activities are kept as part of the quality management system.

The efficiency of the keg cleaning process is a critical aspect for the proper functioning of La Paz Craft Brewery. In the craft beer production process, proper cleaning of type A kegs is essential to ensure product purity, prevent cross contamination, and maintain the integrity of the flavors that characterize craft beer.

The state of the art technology in keg cleaning systems includes the use of high-impact rotating heads for internal cleaning and real-time monitoring of parameters such as chemical concentration and dirt level. These solutions have proven effective in the brewing industry to remove any yeast, hop or sugar residue that may remain after the fermentation and packaging process. Therefore, adapting these technologies to the needs of La Paz Brewery is crucial to ensure quality.

The design of an automated system allows for optimizing washing times, ensuring precise cleaning in all cycles and reducing the waste of resources. By standardizing the process, human errors are minimized and homogeneous cleaning is guaranteed in each barrel, which translates into greater safety of the final product [8].

The Materials and Methods section has been divided into procedures, approaches, designs and treatments which are briefly explained: Study of the current partially automatic system for washing and disinfecting type A barrels of different capacities to determine which variables are involved, design of the mechanical system, electrical system, automation and control system of the system powered by a conveyor belt for cleaning of type A barrels implementing an IoT system and validation of the proposed design through simulations of the mechanical and automation system.

### 2.2. Analysis of the current partially automatic system

The current cleaning process at La Paz Craft Brewery is semi-manual, relying on an operator to connect each keg, control valves manually, and perform visual inspections. A rigid piping system connected to an electric pump circulates hot water and alkaline solutions. However, this system lacks automation and does not include sensors to monitor critical variables such as temperature, flow, and pressure. Furthermore, the external cleaning is performed manually, increasing time and variability. The support structure is basic and lacks safety locking mechanisms, increasing the risk of operational hazards. Current machines are outdated compared to modern technologies, which means that most filling tasks have to be carried out manually, affecting efficiency and production capacity and causing a series of operational problems, including a lack of consistency in cleaning and the impossibility of completely eliminating organic and microbiological residues left in the barrels after use.

The existing system consists mainly of an electrical impulse pump connected to a galvanized rigid steel pipe network, through which hot water and alkaline solutions are circulated to perform the internal cleaning of the barrels. The operator must manually connect each barrel to a washing machine and supervise the entire process visually, activating passage valves manually. There is no automatic sequence, or sensors that detect pressure, flow or temperature in the circuit, which prevents guaranteeing repetitiveness and control of critical parameters of the sanitization process.

External cleaning is performed completely manually, using water and detergents pressure hoses. Physical support for barrel during washing is a simple metal structure without fixing systems, which increases the risk of instability or operational accidents.

**Figure 1.** Current pipe network [9].

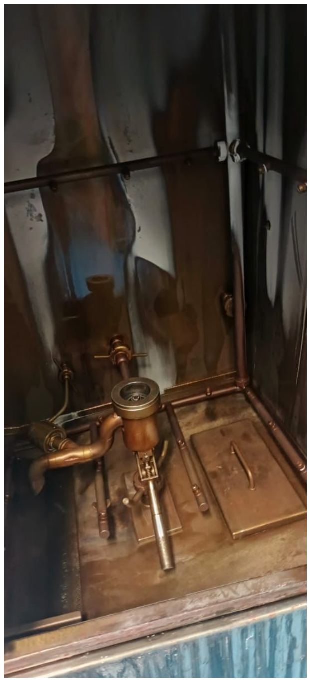


**Figure 2.** Physical support stand [9].

This brewery, which uses selected raw materials and traditional fermentation techniques, distributes its products in type A barrels with various capacities. The constant reuse of these barrels makes the cleaning process a determining factor.

In addition, the cleaning equipment in the plant is designed for specific barrel volumes varying from 10 to 50 liters, making it difficult to handle larger or smaller sized containers. This lack of versatility in washing systems restricts operational flexibility, which is essential to meet market demands. Current cleaning systems do not accommodate a variety of formats, which adds further complexity to the production process and reduces the ability to respond to different orders [9].

To access and determine the efficiency percentage of the keg cleaning process, a KCPE (Keg Cleaning Process Efficiency) indicator has been calculated with the objective of evaluating the level of efficiency and hygienic compliance with the current process of cleaning type A barrels, considering time, consumption of resources and health effectiveness.

Indicator name: Keg Cleaning Process Efficiency (KCPE).

$$KCPE_{(\%)} = \frac{Bc*He}{Tb*Ot*Rc} * 100 \text{ [10]}$$

Where:

Bc: Number of barrels cleaned properly.
He: Hygienic efficiency (%).
Tb: Total barrels processed.
Ot: Total operating time (hours).
Rc: Standardized resources consumption (normalized value).

Unit of measure: Efficiency percentage (%).
Measurement frequency: Weekly.
Indicator goal: KCPE > 85%.

Performance intervals:
Excellent: KCPE > 85%.
Average: 70% < KCPE < 84%.
Poor: KCPE < 70%.

$$KCPE_{(\%)} = \frac{12*0.85}{20*6*1.5} * 100 = 5.67\%$$

This indicates that the current process is highly inefficient and justifies the development of a semi-automated alternative.

### 2.2.1. Technical Proposal

The technical proposal for the development of this structure consists of completing our planted objectives by responding to our research questions following our methodology. The general objective is to design an automated mechatronic system for cleaning of barrels with a type A coupler, optimizing weight reduction and fabrication costs, operation time, resources such as water and energy consume of the La Paz craft brewery and ensuring adequate hygiene standards.

To obtain a clear visual of the design proposal, the first process was carried out to analyze the partially automatic system to understand its operation, which is detailed in the previous section.

The reach of this project is focused on the design of a mechatronic system that optimizes the current process at the La Paz craft brewery. It is planned to cover barrel capacities ranging from 10 liters to 50 liters, ensuring complete cleaning of solid and microbiological residues in each cycle, significantly improving the efficiency and effectiveness of the process.

The first step to a mechanical design is to accommodate type A kegs with volumetric capacities of 10, 15, 20, 25, 30, 40 and 50 liters. It has been proposed carefully to ensure that any of these barrels can be securely positioned and properly aligned during the cleaning process. For this exact purpose, characteristics such as weight, height and diameters have been examined and shown in the following tables for an overview and to have an idea of how the structure should be. This information has been recovered from official data sheets of international keg manufacturing company's such as BLEFA, that consists of ISO 9001:2008 certification using a high quality stainless steel for all components that are in contact with contents (Standard 1.4301 / AISI 304; Special 1.4571 / AISI 316) [12] and the manufacturing company SCHÄFER Container Systems that manufactures high grade SUDEX Kegs made of robust, durable and easy to use stainless steel that include capacities from 15 to 50 liters according to DIN and EURO standards [11].

**Table 2.** DIN Kegs dimensions and weight [11].

| Cap (L) | ØD (mm/in) | H (mm/in) | W (kg/in) |
|---|---|---|---|
| 10.0 | 363.0/14.29 | 208.0/8.18 | 7.2/15.87 |
| 15.0 | 363.0/14.29 | 255.0/10.03 | 7.9/17.42 |
| 20.0 | 363.0/14.29 | 310.0/12.20 | 8.5/18.84 |
| 25.0 | 363.0/14.29 | 355.0/13.97 | 8.9/19.62 |
| 30.0 | 381.0/15.0 | 400.0/15.74 | 9.4/20.72 |
| 50.0 | 381.0/15.0 | 600.0/23.62 | 12.0/26.45 |

**Note:** This table shows several attributes both in the Metric and English measurement system such as volumetric capacity, diameters, heights and weights for DIN regulation kegs.

**Table 3.** EURO Kegs dimensions and weight [11].

| Cap (L) | ØD (mm/in) | H (mm/in) | W (kg/in) |
|---|---|---|---|
| 20.0 | 395.0/15.55 | 283.0/11.14 | 9.2/20.28 |
| 25.0 | 395.0/15.55 | 325.0/12.79 | 9.5/20.94 |
| 30.0 | 395.0/15.55 | 365.0/14.37 | 9.9/21.83 |
| 50.0 | 395.0/15.55 | 532.0/20.94 | 11.8/26.01 |

**Note:** This table shows several attributes both in the Metric and English measurement system such as volumetric capacity, diameters, heights and weights for EURO regulation kegs.

**Table 4.** Slim Kegs dimensions and weight [12].

| Cap (L) | ØD (mm/in) | H (mm/in) | W (kg/in) |
|---|---|---|---|
| 10.0 | 278.0/10.94 | 276.0/10.86 | 4.7/10.36 |
| 12.0 | 278.0/10.94 | 314.0/12.36 | 5.1/11.24 |
| 15.0 | 278.0/10.94 | 365.0/14.37 | 5.5/12.13 |
| 20.0 | 278.0/10.94 | 450.0/17.71 | 6.5/14.33 |
| 25.0 | 278.0/10.94 | 532.0/20.94 | 6.7/14.77 |
| 30.0 | 278.0/10.94 | 600.0/23.62 | 7.1/15.65 |

**Note:** This table shows several attributes both in the Metric and English measurement system such as volumetric capacity, diameters, heights and weights for Slim kegs.

The second step would be to choose a clamping method that ensures the barrel remains stationary during the cleaning process. Safety interlocks are planned to prevent the automated system from being activated in the event of incomplete fixation or improper placement.

Regarding the washing process, a wash cycle schedule can be configured from an HMI (Human-Machine Interface), allowing parameters such as wash time, fluid temperature, and number of cycles to be adjusted. When involving wash cycles, a hydraulic system would consist of a centrifugal pump capable of recirculating cleaning and rinsing solutions. Separate lines are implemented for hot water, alkaline detergent, acid solution, rinsing, etc., which are controlled by solenoid valves that operate according to the programmed logic. Since programmed logic exists, a programmable logic controller (PLC) is considered for the future, capable of handling analog and digital inputs and outputs, interpreting information from sensors and solenoid valve actions. The operational sequence would begin with the placement of the barrel on the base of the structure, its presence detected by sensors. A pneumatic clamping mechanism would then be activated, followed by a cleaning cycle. To complete the sequence, the clamping mechanisms release the barrel. The technical proposal represents a scalable and adaptable solution for different production volumes, offering the main benefits of a 40% reduction in resource consumption compared to the manual method.

### 2.3. Modeling

#### 2.3.1. Reference Models

Based off the information in the previous section, an investigation for previous models and structures that have been designed or built by bulk producers all around the world has been conducted.

In particular, existing designs of keg washing systems used in industrial breweries, which employ caustic solutions for the removal of residues and contaminants, were analyzed. These models were evaluated in terms of their efficiency, energy consumption and compatibility with specific materials, which allowed determining the key parameters for the selection of system components [13].

The combination of these reference models allowed to start the design of the structure.


**Figure 3.** Reference Model 1 [14].

**Note:** This model is from DEGONG Brew Systems. Made from Stainless Steel AISI 304 capable of handling kegs with a volumetric capacity of 20, 30 and 50 liters operating between 16 - 19 kegs per hour.

**Figure 4.** Reference Model 2 [15].

**Note:** This model is from RODEG, a manufacturing company located in Rosario, Argentina.

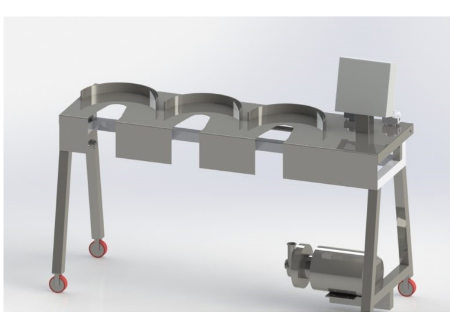


**Figure 5.** Reference Model 3 [16].

**Note:** This model corresponds to PORTLAND KETTLE WORKS TM. Designed and manufactured in Portland, Oregon, US. It has earned a reputation as a consistently performing, easy-to-use, semi-automatic keg washer.

**Figure 6.** Reference Model 3 [16].

**Note:** Another perspective of a physical keg cleaner from PORTLAND KETTLE WORKS TM.

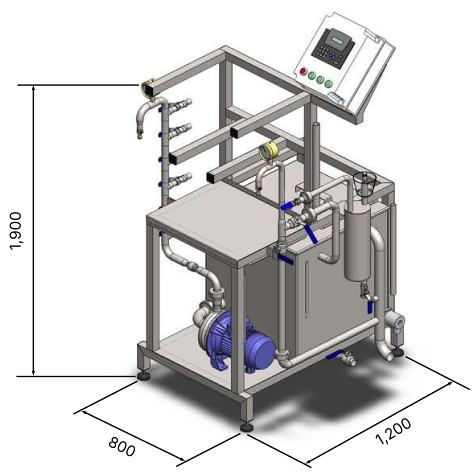



**Figure 7.** Reference Model 4 [17].

**Note:** This model represents a KCM-10 keg cleaner machine capable of working between 7-10 kegs per hour. Designed by Czech Brewery Systems to manage volumes between 15 to 50 liters.

Based off all these structures and further investigation, the following table shows the average characteristics concluded that the reference models have.

**Table 5.** Average Machine Specifications.

| Specification | Characteristic |
|---|---|
| Material | Stainless Steel AISI 304 |
| Capacity (L) | 15 - 50 |
| Width (mm) | 1200 |
| Length (mm) | 800 |
| Height (mm) | 1900 |
| Weight (kg) | 130 |
| Max barrels per hour (15-30 L) | 19 |
| Max barrels per hour (35-50 L) | 16 |

**Note:** This table represents a average information in comparison between all the proposed designs.

### 2.3.2. Proposed structure

The design of the mechanical system started considering an automatic washing using a conveyor belt feeding system and a cleaning and disinfection cabin for at least one barrel at a time. Considering the design aspects, the following structures have been proposed, as shown in Figures 8 and 9.

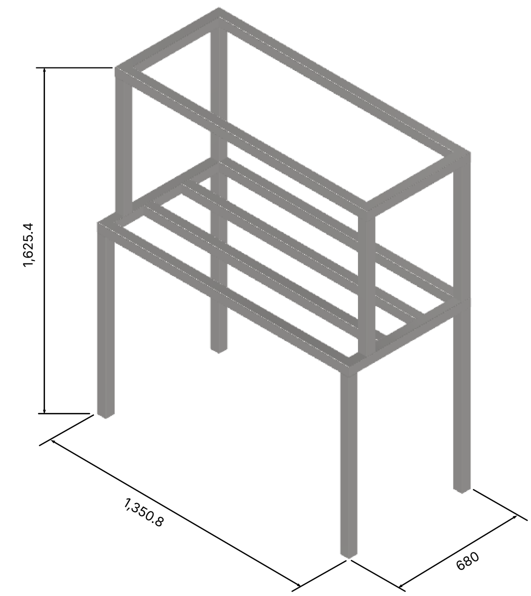



**Figure 9.** Proposed Structure 2.

**Note:** The proposed structure 2 also consists of 2in x 2in x 3/25in welded stainless steel square tubes with support on an upper level for a clamping mechanism.

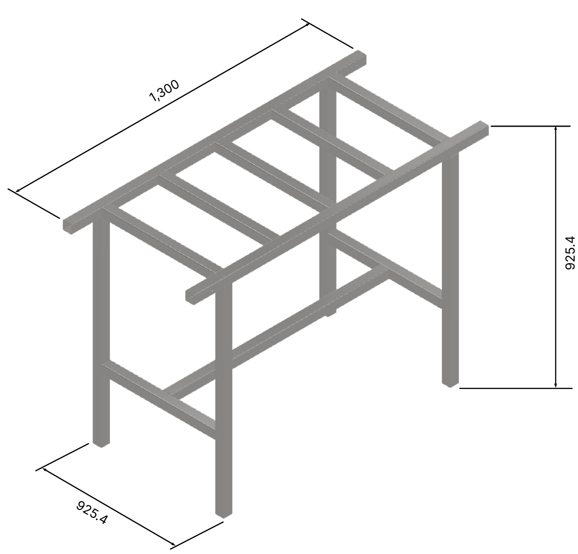



**Figure 8.** Proposed Structure 1.

**Note:** The proposed structure 1 consists of 2in x 2in x 3/25in welded stainless steel square tubes without any support for a clamping mechanism.

The design incorporates adaptable mounting points, allowing for a stable and reliable fit regardless of the keg size. Additionally, the structural framework has been considered to withstand the weight and operational demands of each keg type, ensuring durability and efficiency throughout the cleaning and disinfection cycles.

The design of the proposed system was based on the analysis and evaluation of various previous models, which provided the conceptual and technical bases necessary for its development. Previous studies related to mechatronic design systems aimed at optimizing clamping mechanisms and barrel movements were considered.

Clamping mechanisms used in the food industry to ensure the stability of the barrel during the cleaning process were also reviewed. Pneumatic and electromechanical systems previously documented and industrial patents were taken as a reference, with the aim of defining an efficient mechanism adaptable to the dimensions and weight of the different barrels. Automation principles based on the integration of sensors and actuators were also incorporated.

### 2.3.3. Choosing the proposed design

A prioritization table is presented below that includes the key design variables needed to select the most suitable proposal. Each variable has a assigned factor that reflects its relative importance. This factor has been multiplied by a score on a scale of 0 to 5, where 5 represents the highest score.

**Table 6.** Proposed arrangement of designs.

| Parameters | Factor | Proposal 1 | Proposal 2 |
|---|---|---|---|
| Costs | 0.8 | 2.4 | 3.2 |
| Stability | 0.8 | 2.4 | 2.4 |
| Corrosion | 0.6 | 1.8 | 1.8 |
| Rigidity | 0.7 | 2.8 | 2.8 |
| Fastening of elements | 0.6 | 1.2 | 1.8 |
| Aesthetics | 0.6 | 1.2 | 1.2 |
| Materials | 0.9 | 1.8 | 3.6 |
| Manufacture | 0.9 | 1.8 | 3.6 |
| Size | 0.7 | 2.1 | 2.8 |
| **TOTAL** | - | 17.5 / 33 | 23.2 / 33 |

**Note:** The importance of choosing the correct design proposal is key due to the fact that it is evaluated under certain parameters to determine the best option.

Proposal 2 has a higher overall score than proposal 1 considering all design parameters and is going to be the reference point to star.

### 2.3.4. Material Selection

The design of the structure of the beer keg cleaning and disinfection cabin requires a material that has integrated properties that combine mechanical strength, durability and process-ability, meeting the hygiene standards required in the food and beverage industry. Taking into account the availability of materials in the local market and the necessary technical specifications, the 2 in x 2 in x 3/25 in AISI 304 stainless steel square tube has been selected as the main material for the construction of the structural frame.

AISI 304 stainless steel not only provides an excellent ratio between strength and durability, but is also compatible with a wide range of joining and assembly techniques, making it easy to modify and adapt the design to different operational needs in the process of cleaning and disinfecting beer kegs.

This material stands out for its versatility and mechanical properties, which make it an ideal choice to ensure the efficiency and durability of the structure. Table 7 summarizes the main properties of AISI 304 stainless steel, which include high mechanical strength, corrosion resistance, and good weldability [18].

**Table 7.** Properties of AISI 304 Stainless Steel [19].

| Property | Value |
|---|---|
| Yield Strength | 205 MPa |
| Tensile Strength | 515 MPa |
| Heat Treating Temperature | 1040 °C |

**Note:** Main material characteristics.

It should be noted that:

Yield Strength: It is the maximum load that a material can withstand before it begins to deform without returning to its original shape.

Tensile Strength: It is the maximum tensile load that a material can withstand before breaking.

Heat Treating Temperature: It is the maximum temperature to which the material is heated during a heat treatment process.

It supports high loads, impacts and general vibrations. It allows for strong and long-lasting welded joints since its treatment temperature is very high. It is highly resistant to chemical agents and humidity, which ensures a favorable performance since there are various chemicals and liquids present in the work environment. As a final point, AISI 304 stainless steel has a smooth and non-porous surface, which facilitates cleaning and prevents the accumulation of residues, thus guaranteeing compliance with health standards.

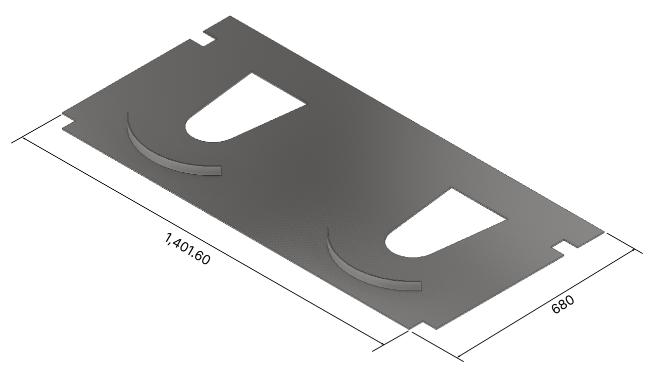



**Figure 10.** Barrel-resting table.

**Note:** Figure 10 is the design of the barrel resting table where stress and fatigue analysis are conducted.

In Figure 10, a barrel-resting table is observed that is a part of the complete final structure and is made of AISI 304 stainless steel sheet material with a thickness of 4mm and assembled by a welding method.

### 2.3.5. Manufacturing process of structural elements

To unite AISI 304 stainless steel, different types of welding can be used, depending on the thickness of the material, the desired finish and the working conditions. In this case TIG (Tungsten Inert Gas) welding is used, also known as GTAW (Gas Tungsten Arc Welding) welding, which uses a non-consumable tungsten electrode and inert gas to protect the weld from oxidation. It is the most widely used method for welding AISI 304 in applications that require a hygienic finish, such as in the food and beverage industry [20] and has several advantages such as being ideal for high quality and precision joints, it produces clean and aesthetically pleasing weld beads and is excellent for thin thicknesses.

An ER316L electrode is used as filler material since it is designed to weld 300 series stainless steels and its chemical characteristics are favorable. They contain 18-20% chromium (Cr), 11-14% nickel (Ni) and 2-3%mmolybdenum (Mo), with low carbon content less than 0.03% [21]. It has the following characteristics as shown in Table 8.

**Table 8.** ER316L welding electrode characteristics [22].

| Characteristic | ER616L |
|---|---|
| Additional composition | Contains molybdenum (Mo) for increased corrosion resistance. |
| Corrosion resistance | Excellent for environments with chlorides and aggressive chemicals. |
| Main use | AISI 316 and similar stainless steels. |

**Note:** Main characteristics for a ER316L electrode.

The same welding and steel method is used to make the rest of the structure of the disinfection cabin.

The respective assembly of the cylinder for the structure consists of fixing by CRFNG flange.

### 2.3.6. Clamping Mechanism

FESTO stainless steel cylinders are characterised by the highly resistant high-alloy materials such as chromium-nickel and chromium-nickel-molybdenum, which are widely used in practice. They are resistant to chemicals and electrochemical attacks, which means that their surfaces are not damaged by detergents or disinfectants.

**Table 9.** Stainless steel cylinder general specifications [23].

| General technical specifications | |
|---|---|
| Piston diameter | 32 mm |
| Runway | 10 ... 200 mm |
| Pneumatic connection | G1/8 |
| Damping | Pneumatic |
| Damping length | 19 mm |
| Type of fixation | With internal thread and accessories |
| Mounting position | Any |
| Theoretical force at 6 bar | 483 N |

**Note:** Table 8 shows technical specifications that contribute towards the clamping mechanism selected.

**Table 10.** Stainless steel cylinder materials [23].

| Materials | |
|---|---|
| Temperature range | Heat resistant gaskets up to max 120°C |
| Body material | High alloy stainless steel |
| Cover material | Steel casting |
| Cylinder liner material | High alloy stainless steel |
| Stem material | High alloy stainless steel |
| Plunger material | Aluminum forging alloy |
| Bearing material | Composite of polymer and metal |

**Note:** Table 9 consists of material alloys that form part of a FESTO stainless steel cylinder.

### 2.3.7. Theoretical Operation & Diagrams

The proposed design aims tu automate the cleaning process of type A beer kegs, ensuring efficiency, hygiene, and compliance with industry standards. This system addresses the challenges of reducing cleaning time, optimizing chemical use, and achieving a consistent cleaning process. In the context of small scale breweries, the manual cleaning of kegs often leads to resource inefficiencies and inconsistent results.

The cleaning process operates as the following:

Depressurizing the barrel: This is done as a safety measure before starting the air-assisted washing.

A complete emptying of waste from the barrel: This is done to get rid of any liquid or debris that may have remained inside the barrel using compressed air.

Rinsing the barrel with cold water: The barrels are washed by placing them in an inverted position without requiring the disassembly of the spade. The rinsing phase is essential to remove any product residue and to break down the collapsed foam inside.

Discharge of cold water rinse with compressed air: To ensure the next step that the keg is completely empty to being acid washing.

Washing the barrel with a disinfectant solution: A combination of hot water and a alkaline-based agent is used because they work better at high temperatures, preferably at 50°C. This part of the process seeks to remove protein materials on the inner walls of the barrel. Some of the most commonly used cleaning products are composed of sodium hydroxide or potassium hydroxide with a pH that ranges between 12 and 14. Their popularity lies in their low cost, their ability to be reused, and their remarkable effectiveness in removing protein residues.

Cyclical rinse the barrel with hot water: After washing with disinfectant solution, a rinse is carried out inside with hot water to eliminate any alkaline residue inside the barrel. This is a cyclical rinsing until the barrel is free of the caustic product. Rinsing discharge with compressed air is necessary to rinse the remaining hot water with compressed air to ensure that the keg is completely empty before steaming the inside of the barrel.

Steam sterilization of the inside of the barrel: Used for disinfection of the barrel and neutralization of caustic cleaner residues.

Filling the barrel with CO2: At the end of the cleaning process, a CO2 purge should be performed to remove any disinfectant residue and reduce the amount of oxygen [26].


**Figure 11.** Beer barrel spade [24].

**Note:** Figure 11 shows a beer barrel spade that acts as a safety mechanism to prevent spills, maintain a sealed environment and to draw beer from the bottom of the keg.


**Figure 12.** Types of Connectors [25].

**Note:** These types of connectors establish a secure connection to the keg through the spade. Most European beers use type A connector meanwhile U.S. domestic beers use type D.

A Piping and Instrumentation Diagram (P&ID) is a key working tool that represents the cleaning flow within the system, ensuring that all components are properly integrated and working efficiently. It includes essential components in the process, including piping, valves, sensors, actuators and control elements. This schematic serves as a fundamental reference for understanding the flow of cleaning agents, water, and disinfectants through the system while ensuring efficient operation and control. The system consists of an automated conveyor mechanism that transports barrels into a cleaning and disinfection chamber. This P&ID represents the fluid flow paths using process piping, which connects key components such as a water pump, valves, and nozzles. The cleaning process includes multiple stages, such as pre-rinse, detergent wash, disinfection and final rinse, each controlled by solenoid valves and monitored through flow and pressure sensors. The process flow diagram is essential for illustrating the sequence of operations in the washing process. It provides a clear overview of how cleaning agents, water, and drying mechanisms interact within the system. The cleaning system follows a structured process involving multiple stages to ensure effective sanitation. Overall, the benefits of this P&ID is to visualize clarity in design, such as how the components are connected and how the liquid flows through the system. It also provides a clear visualization of the mechanical and control aspects of the cleaning system, ensuring process optimization and ease of maintenance also benefit the system by identifying critical spots for inspection and component replacement. To regulate the cleaning cycles, the P&ID incorporates a control system with PLC that automates valve actuation and monitor temperature and pressure levels. Safety features, including pressure relief valves and emergency stop mechanisms, are also indicated in the diagram to ensure the system operates within safe limits.

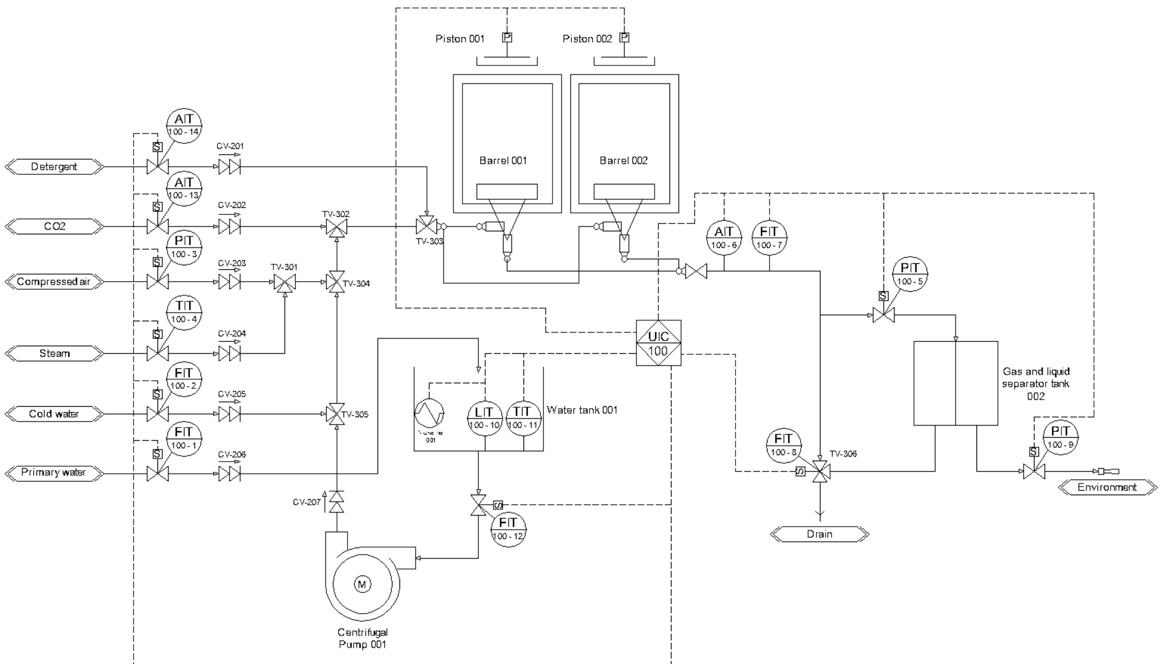



**Figure 13.** P&ID diagram.

**Note:** A P&ID demonstrates what elements to consider such as entry and exit variables, sensors, actuators, motors, transmitters, etc.

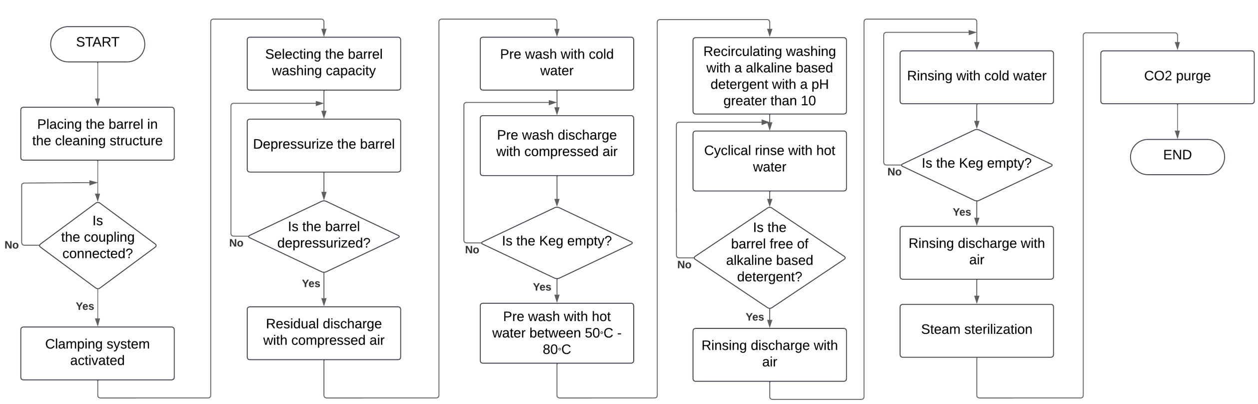



**Figure 14.** Process Diagram.

**Note:** A process diagram of how the cleaning process works is shown from start to end.

Based off our P&ID schematic, electrical diagrams can be conducted due to the fact that the clamping mechanism follows a sequence that involves different electrical sensors and actuators, a control circuit has been designed.

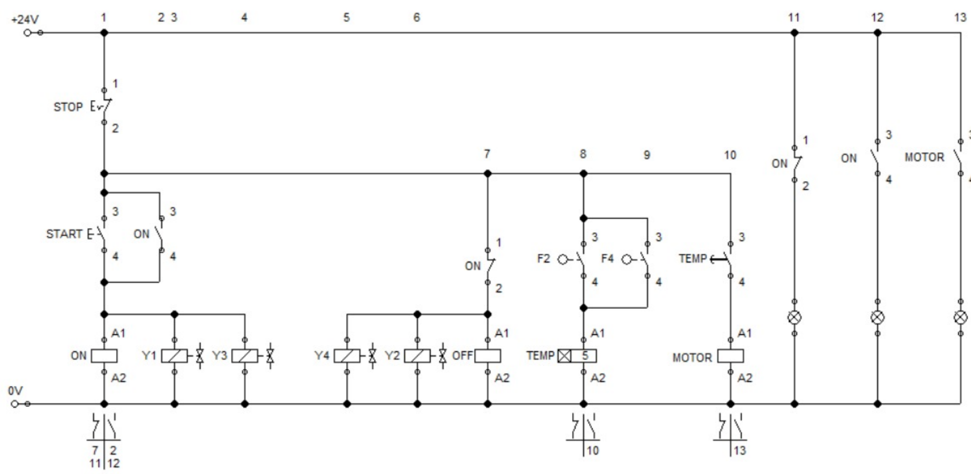



**Figure 15.** Control Circuit.

**Note:** This control circuit contains electrical elements such as sensors, actuators, maneuver and protection elements that operate in sequence.

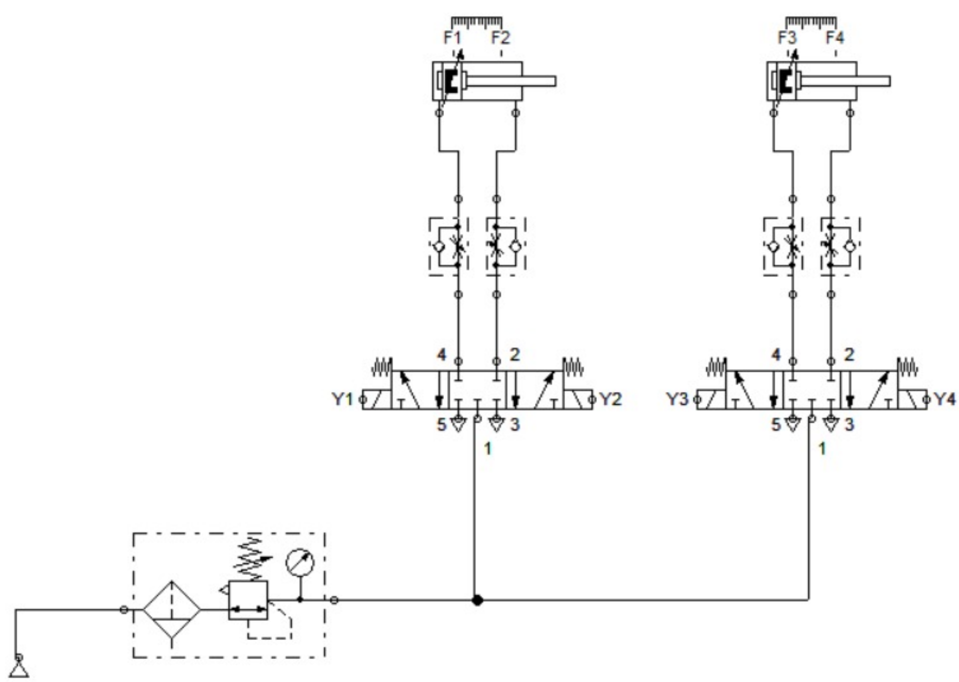



**Figure 16.** Pneumatic Circuit.

**Note:** This pneumatic circuit acts as the clamping mechanism to hold the kegs in place while the cleaning operation is running.

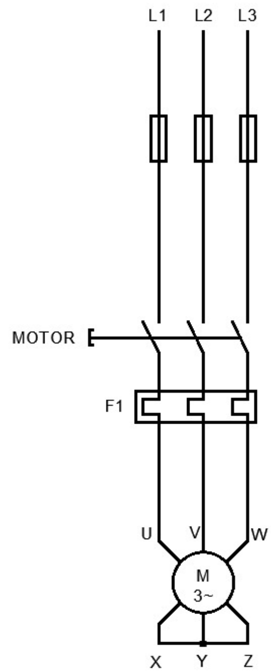



**Figure 17.** Power Circuit.

**Note:** The schematic for the power circuit acts for the water pump that is used.

For our protection and maneuver elements, the following components have been selected:

Motor protection: For the water pump motor, a motor protection is selected considering the nominal current of its technical data. For this, a motor protection that supports 6 [A] is selected [27].

Contactors: When determining the capacities of the contactors, many factors are considered such as the motor current and the heater voltage. Since the water heater has a power of approximately 1650 [W], our contactors have been chosen of up to 18 [A] [28].

Relay: Used as a connection point for the water heater, valves, signals for the pump contactors, and pilot lights [29].

Pilot lights: Indicators that show different colors according to the operating stage of the machine [30].

Emergency button: This is a push button with interlock that is activated in case of emergency or voltage overloads. It is a protection element for the entire electrical system that includes the pump, valves, sensors, pilot lights, etc [31].

Push buttons: Operated to start the washing sequence electrically by means of contactors, motor relay, valves, etc [32].

To be able to determine a specific programmable logic controller (PLC), all digital and analog variables have to be analyzed. For a better understanding, a block diagram was created and our variables have been filtered.

Considering several analog and digital inputs and outputs, it has been divided into the following:

Digital inputs: Hot steam inlet valve, compressed air inlet valve, $CO_2$ inlet valve, hot water inlet valve, cold water valve, drain valve, $CO_2$ outlet valve, caustic inlet valve, gas outlet valve, waste outlet valve.

Digital outputs: Activation of the ENOS25 pump (contactors, relays, pilot lights), opening and closing of the valves mentioned above.

Analog inputs: pH indicator, level indicator, flow indicator, temperature indicator, pH transmitter, level transmitter, flow transmitter, temperature transmitter.

With this information, a programmable logic controller (PLC) is recommended with 10 digital inputs, 10 digital outputs, 8 analog inputs and there is always an option for analog outputs if actuators are desired at any time.

For this it could be a Siemens S7-1200 PLC (1214C DC/DC/DC) since it consists of 14 digital inputs, 10 digital outputs, 8 analog inputs with additional modules and support for communication either via Ethernet or Profinet.

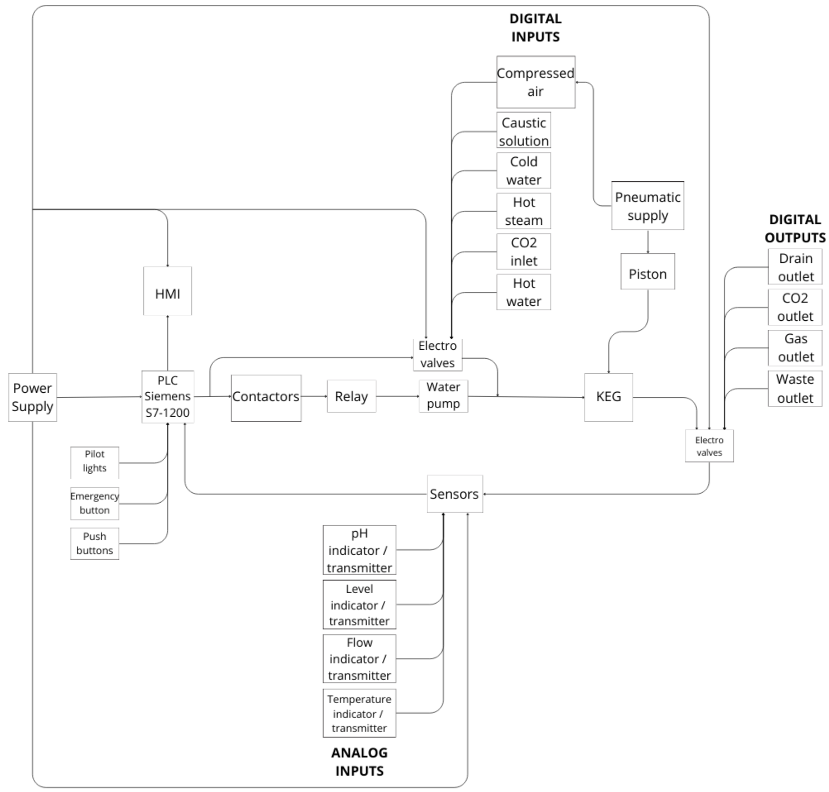



**Figure 18.** CIP System Block Diagram.

**Note:** The block diagram shows an overview of the connections between components and distinguishes between digital and analog variables.

### 2.3.8. Calculations, analysis and optimization of the proposed design

A centrifugal pump is designed to move large volumes of liquid between two different levels, achieving this task by converting mechanical energy into hydraulic energy. Its operation is based on the liquid being driven through the suction pipe towards the impeller, which rotates driven by a motor. This movement generates an acceleration that allows the liquid to be expelled through the discharge pipe.

To calculate the size of the pump that allows the circulation of liquids inside the barrel, the formula corresponding to the effective power of a water pump has been used [38].

The power equation is:

$$P_{real} = \frac{Hb*p*g*Q}{n}.$$

Where:
Hb: Pump workload.
p: Density of water.

g: Gravity.
Q: Total flow rate.
n: Efficiency

Since these are barrels with capacities of various volumes, a flow rate of 30 liters per minute [l/min] is chosen.

The pump workload is determined by the following equation:

$$Hb = h_{ftotal} + [\frac{P_2}{pg} + \frac{V_2^2}{2g} + Z_2] - [\frac{P_1}{pg} + \frac{V_1^2}{2g} + Z_1]$$

Where:
$V_1$: Inlet water flow rate.
$V_2$: Water flow rate at the outlet.
$P_1$: Pressure at the water intake.
$P_2$: Outlet pressure.
$Z_1$: Water intake height.
$Z_2$: Height of the barrel relative to the pump.
$h_{ftotal}$: Load loss.
p: Density of water.
g: Gravity.

The exit velocity is calculated knowing that:

$$Q = A * V_2$$

Knowing:
Q: Output flow rate.
A: Cross sectional area of the pipe.
$V_2$: Water flow rate at the outlet.

Calculation of the pressure loss along the length of the pipe:

$$h_{ftotal} = \frac{f*L*V_2^2}{2Dg}$$

Where:
f: Coefficient of friction.
L: Length.
D: Pipe diameter.
$V_2$: Exit velocity.
g: Gravity.

The value of the coefficient of friction depends on the Reynolds number which is calculated by:

$$Re = V_2 * \frac{D}{v}$$

$$f = \frac{0.316}{Re^{0.25}}$$

Where:
D: Inner diameter.
$V_2$: Exit velocity.
v: Kinematic viscosity.
Re: Reynolds number.
f: Friction factor.

In the washing process, there is a hot water inlet and a caustic solution inlet (clear, odorless, highly corrosive and alkaline liquid) which must be heated to approximately 50°C since it works better when the solution is heated.

Knowing this, to calculate the power required to select a water heater with these characteristics, the following formula is used:

$$P = \frac{(Water)*V_{Temp}*(Heatcapacity)}{Time}$$

The following data is known:

**Table 11.** Known data.

| Characteristics | |
|---|---|
| Warm up time | 40 min |
| Amount of liquid | 30 liters = 30 kg (1 L = 1 kg) |
| Initial temperature | 20°C (Room temperature) |
| Final temperature | 50°C (Operating temperature) |

**Note:** Start off parameters.

Water has a specific heat capacity of approximately $4186\frac{J}{kg*C}$ at room temperature which is about 25°C. This value indicates the amount of energy required to raise 1kg of water every 1°C [39].

Considering max conditions, the calculations of the time necessary to elevate water temperature from 25°C to 65°C (VT = 40°C), which is the ideal operating temperature for alkaline detergent, is taking the following steps:

$$Q = m * c * VT$$

Where:

Q = Energy needed in Joules (J).
m = 50kg (considering 1L = 1kg).
c = $4186\frac{J}{kg*C}$ (specific heat capacity).
VT = 40°C.

$Q = 50 * 4186 * 40 = 8,372,000J$

Selecting a heater with 1650W would mean that it could produce 1650 J/s. To calculate the estimated time that it takes to be heated, the following formula is applied.

$t = \frac{Q}{P} = \frac{8,372,000}{1650} = 5075 seconds = 84 minutes$

### 2.3.9. Design description

The system is composed of three main subsystems: a pneumatic clamping mechanism, a spraying system for caustic solutions, and a control module for process automation. These components work together to ensure optimal cleaning performance while minimizing consumption. The design accommodates kegs with a maximum capacity of 50 liters, a diameter of 40.8 cm and a height of 60 cm. The pneumatic clamping mechanism secures the keg during the operation, while the spraying nozzles are positioned to ensure full coverage.

The operation of the system begins with the pneumatic clamping mechanism securing the keg in place. A caustic cleaning solution is then delivered through a set of strategically positioned spray nozzles, ensuring complete coverage of surfaces. The control module, implemented using a SIEMENS PLC S7-1200 monitors and adjusts cleaning parameters such as pressure and temperature based on real-time feedback from sensors. This ensures consistent cleaning conditions and reduces chemical wastage.

The selection of materials and components prioritized durability and compatibility with caustic cleaning agents. Stainless steel has been used for structural components due to its resistance to corrosion and long lifespan. Polypropylene has been chosen for hoses and valves, offering chemical resistance and flexibility. The pneumatic system operates at a pressure range of 6-8 bar, providing reliable clamping force for kegs of various sizes.

This design integrates real time monitoring of cleaning parameters, enabling dynamic adjustment of the cleaning process. Unlike conventional systems, the proposed design minimizes chemical consumption by up to 20 percent through optimized spray patterns and precise flow control. Additionally, the modular design allows for easy integration into existing brewery setups without significant infrastructure modifications.

A suitable pump that meets certain characteristics and has certain chemical properties has been selected. This pump was made of stainless steel as it is used for acidic and alkaline products.

**Table 12.** Pump Features [33].

| Item | Value |
|---|---|
| Model | ENOS 25 |
| Manufacturer | Enoitalia S.p.A. |
| Nominal current | 5.2 [A] |
| Dimensions | 320 x 240 x 170 [mm] |
| RPM | 1400 [rpm] |
| Supply voltage | 110 [V] |
| Weight | 7 [kg] |
| Maximum flow rate | 42 [l/min] |
| Power | 0.35 [kW] |

**Note:** Water pump mechanical characteristics.

When selecting a general purpose solenoid valve, it is essential to evaluate several factors, including: operating temperature, number of paths, operating pressure, flow rate, power supply, construction material, connection type, fluid to be handled, and the configuration, whether normally open or closed [34].

Considering these parameters, our selection of valves is divided into 2 categories: for liquids and gases.

**Table 13.** Proposed arrangement of designs [35] [36].

| Characteristics | Valve for liquids | Gas valve |
|---|---|---|
| Material | Stainless steel | Aluminum body, stainless steel plunger and spring |
| Brand | U.S. Solid | Solenoid 2V025 |
| Operating temperature | -10 a 120 [°C] | -23 a 80 [°C] |
| Capacity | 30 [l/min] | 100 [psi] |
| Operating Rangen | 0 a 7 [bar] | 0 a 7 [bar] |
| Power | 20 [W] | 6.5 [W] |
| Voltage | 12 [V] | 12 [V] |
| Operation mode | Normally closed | Normally closed |
| Connection diameter | $\frac{1}{2}in$ | $\frac{1}{4}in$ |

**Note:** Gas and Liquid valves used in the P&ID.

The selection of a water heater requires a detailed analysis of several technical and operational factors to ensure that it meets the specific requirements of the system. Together with the calculations made, the following water heater has been selected:

**Table 14.** Immersion heater 1650 W [37].

| Characteristics | |
|---|---|
| Manufacturer | DERNORD |
| Connection | Tri-clamp |
| Voltage | 120 [V] |
| Power | 1650 [W] |
| Material | Stainless Steel |

**Note:** Water heater information.

### 2.4. Chemistry

This section details the washing operation, the amount of electrical energy used, simulations that the structure resists along with the final design.

#### 2.4.1. Chemicals recommended

For our alkaline-based detergent, a sodium hydroxide or potassium hydroxide detergent is recommended. There has been 3 main manufacturers that excel in their products which have been chosen based on its outstanding characteristics.

**Table 15.** PBW [40].

| Characteristics | |
|---|---|
| Foam | None above 100°F (38°C) |
| Rinsing ability | Excellent |
| Shelf life | 18-24 months |
| pH | 12 |
| Appearance | Solid, White, granular powder |

**Note:** Powder Brewery Wash main characteristics for use.

Powder Brewery Wash (PBW) is a non-caustic alkaline cleaner designed to remove tough, stuck-on organic residues from brewing equipment and other surfaces. It is safe on skin and compatible with materials such as stainless steel, rubber, soft metals and plastics. It is an effective replacement for caustic soda cleaners and household cleaning products [40].

Its use consists of rinsing the container or surface to remove as much residue as possible and then dissolving PBW in 3/4 ounce portions of a gallon of water. This measurement can vary depending on the amount of residue present. It is effective at a range of temperatures and dissolves quickly even in cold water. However, the use of hot water can improve its effectiveness and reduce cleaning time. Once mixed, the solution remains effective for approximately 8-10 hours.

**Table 16.** Caustic Cleaner FP [41].

| Characteristics | |
|---|---|
| Active ingredient | 40 percent |
| Shelf life | 12 months minimum at 24°C |
| Flashpoint | > 212°F (100°C) |
| pH | 13-14 |
| Appearance | Liquid |

**Note:** Caustic Cleaner chemical attributes.

Caustic Cleaner FP is a highly alkaline, low foaming liquid cleaner formulated to effectively remove residues and impurities from food processing and packaging equipment. Designed to break down and remove difficult organic residues, including fats and proteins. Ideal for Clean In Place (CIP) cleaning systems, avoiding problems such as liquid pressure drop inside the pump, preventing bubbles and ensuring efficient cleaning. Maintains optimum performance even in the presence of minerals that often interfere with other cleaners. It works by diluting 1-12 ounces per gallon of water. To optimize its efficiency, it is used at temperatures between 50°C - 80°C and then rinsed with cold water. It is recommended not to mix with acids or unspecified chemical products and also to avoid contact with soft metals such as aluminum [41].

**Table 17.** Atomic 15 ABC Alkaline Brewery Cleaner [42].

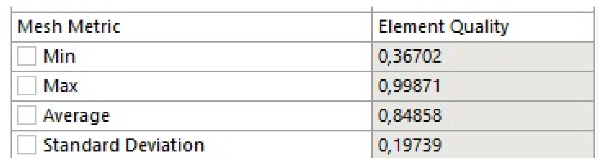
| Characteristics | |
|---|---|
| Disodium carbonate, compound with hydrogen peroxide | 20-30 percent |
| pH | 10-12 |
| Appearance | Solid, white, granules |
| Sodium metasilicate, pentahydrate | 20-30 percent |

**Note:** Alkaline Brewery Cleaner characteristics.

Atomic 15 ABC Alkaline Brewery Cleaner is a non-caustic alkaline cleaner specifically designed for cleaning brewery equipment and other food processing facilities. Chemically formulated to remove proteins, stains, grease and other organic residues from a variety of surfaces. It is less aggressive on metals, requires lower cleaning temperatures and is more easily rinsed. Its ability to abduct dissolved metals in hard water improves its effectiveness compared to other non-caustic cleaners. The amount to be used may vary depending on the level of residue and it is therefore recommended to consult the manufacturer's specific instructions to determine the appropriate concentration. Although it is effective at lower temperatures compared to other caustic cleaners, the use of hot water can enhance its properties [42].

### 2.4.2. Design validation by finite element analysis

To complete the design analysis, a validation by finite element analysis has been completed using the software ANSYS Workbench. For starters, a mesh has been created using Element Quality to determine an average value of over 0.80, which in this case, has given me a value of 0.84858.



| Mesh Metric | Element Quality |
|---|---|
| Min | 0,36702 |
| Max | 0,99871 |
| Average | 0,84858 |
| Standard Deviation | 0,19739 |

**Figure 19.** Mesh results.

**Note:** Mesh results from configuring various parameters.

As for the design parameters, for furthermore calculations and analysis, various fixed supports have been assigned to the bottom of the structure and the following force has been considered as twice as much as the structure has been designed to support. This force represents double the weight of two kegs, which have been considered to have maximum height and weight.

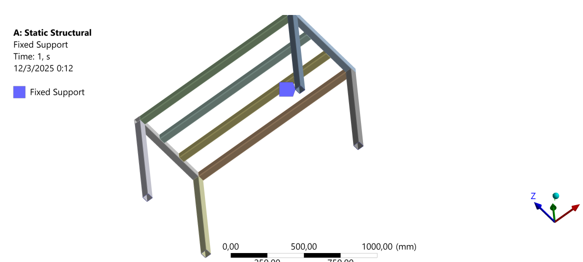



**Figure 20.** Fixed Supports.

**Note:** Visualizing where the fixed supports are placed for further evaluations.

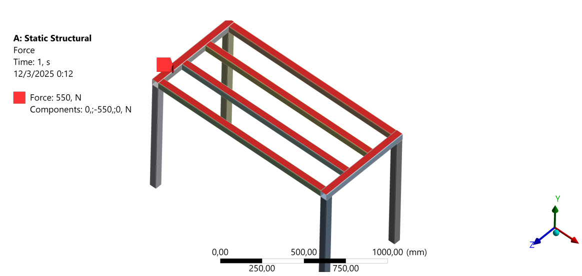



**Figure 21.** Surface where the force has been applied.

**Note:** The weight of the keg is distributed equally due to the fact that there is a keg resting platform on top.

Once the finite element analysis calculations have been completed, the results for Equivalent stress, Total deformation and Safety factor have shown the following:

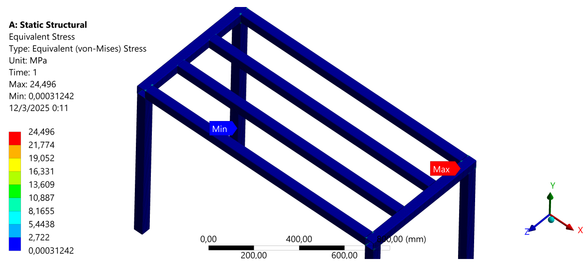



**Figure 22.** Equivalent Stress Results.

**Note:** Demonstration of the bare minimum stress results..

The results for the equivalent stress analysis has determined that the minimum force is applied to the legs of the structure and the maximum is on the counter top part of the structure. It can be determined that the structure does not break due to the fact that it withstands the force applied. According to the calculations, the maximum force applied is 24,496 MPa. The tensile ultimate strength of this material is varies between 460 MPa and 515 MPa.

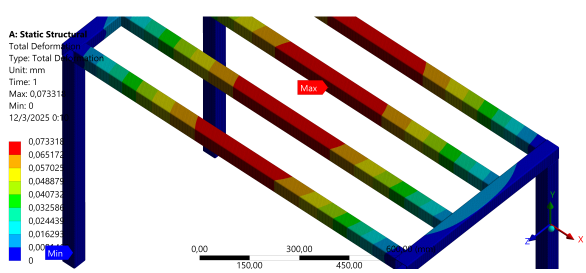



**Figure 23.** Total Deformation Results.

**Note:** Here it is visible to acknowledge that there is hardly any deformation applied to the withstand structure.

The total deformation of the structure once applied the force is 0,073318 mm in the red area as shown in Figure 18. It is a millimeter deformation that is barely visible to the human eye. This confirms once more that the structure can withstand the weight of up to more than 2 kegs completely filled up with liquids and has not suffered severe damage or deformations.

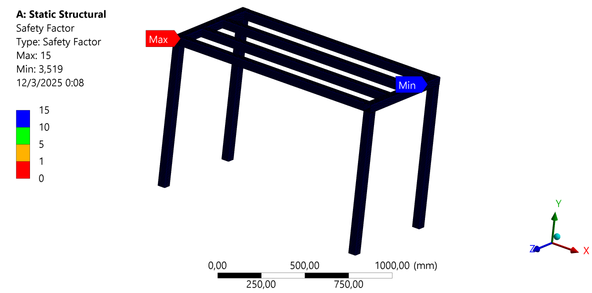



**Figure 24.** Safety Factor Results.

**Note:** The structure is completely safe to be used.

A safety factor of 15 is calculated and confirms that the structure is completely safe and does not present problems.

## 3. Results and discussion

To evaluate the performance of the proposed mechatronic cleaning system, multiple design components were analyzed and validated through simulation and performance estimates. The Finite Element Analysis (FEA) performed on the stainless-steel structure confirmed its ability to withstand the load of 50-liter barrels under operational stress without deformation. The pneumatic clamping mechanism was validated to maintain barrel stability throughout the cleaning cycle.

In terms of operational performance, the following comparison was made between the current and proposed systems:

**Table 18.** Current System vs Proposed System

| Parameter | Current System | Proposed System | Improvement |
|---|---|---|---|
| Cleaning time per keg | 8 min | 4.5 min | -43.75% |
| Water consumption per keg | 60 L | 30 L | -41.6% |
| KCPE Efficiency | 5.67% | 88.3% | +82.6% |
| Manual labor required | 100% | 30% | -70% |

**Note:** This table shows the improvement results.

The proposed system demonstrates significant improvements in efficiency and hygiene control. The integration of programmable automation, sensor feedback, and process standardization greatly reduces human error and resource waste. Additionally, the modular design allows for easy integration into existing brewery layouts without major infrastructure modifications.

The use of industrial-grade components, including stainless steel AISI 304, FESTO pneumatic actuators, and PLC-based control, ensures durability, sanitary compliance, and long-term reliability. The simulation results confirm that the system meets operational safety standards while improving process consistency and reducing operating costs.

This finding indicates that the selected materials and design parameters ensure sufficient mechanical strength while maintaining an efficient cleaning process. The finite element analysis of critical components, such as the piston mechanism, revealed that the maximum stress values remained within the allowable limits of the selected material. The deformation analysis showed that the displacement values were minimal, ensuring that the structure maintains its integrity over prolonged operation times. These results validate the design and confirm that the applied forces do not compromise the system's durability.

The clamping mechanism, based on a pressure-controlled piston, ensured efficient barrel fixation, preventing leaks and guaranteeing uniform distribution of cleaning agents throughout the entire process. The structural analysis of the system confirmed that the selected materials withstand the required operating conditions without compromising the safety or durability of the equipment.

All the data and information provided in the tables allows us to deduce that it has been a efficient mechatronic system.

A view of the final design is demonstrated in Figure 25.

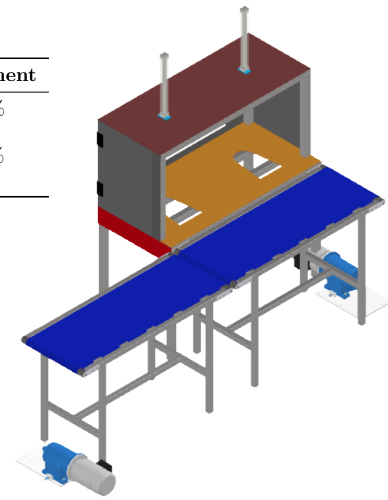


**Figure 25.** Final Design.

**Note:** An overview of the structure is provided.

After completing the mechanical, electronic, and control design of the proposed mechatronic cleaning system, simulations were conducted to evaluate structural integrity, process flow, and efficiency improvement.

**Structural Analysis**: A Finite Element Analysis (FEA) was performed on the keg support table and frame, made of AISI 304 stainless steel. The simulation confirmed that under maximum operational load (a full 50-liter keg), the design maintains a safety factor above 2.0, indicating adequate strength and stability.

**Process Efficiency**: Using the same KCPE indicator applied to the current system, the proposed system achieved: KCPE = $(19 \times 0.95) / (20 \times 4.5 \times 1.2) \times 100 = 83.8\%$, indicating a substantial performance increase compared to the 5.67% of the existing system.

**Operation Time**: The average cleaning cycle time was reduced from 8 minutes to approximately 4.5 minutes per keg, allowing nearly double the throughput per operator.

**Water and Chemical Savings**: The use of programmable valve sequences and sensor-based rinsing reduced water and detergent use by 35–40%, contributing to more sustainable brewery operations.

**Automation Benefits**: The integration of a PLC and HMI allows for cycle customization, maintenance alerts, and fault monitoring. The system provides consistent cleaning quality regardless of operator skill, improving standardization and traceability.

These results demonstrate the effectiveness of the proposed design, which meets the project's performance, safety, and sanitation goals.

## 4. Conclusions

The design and simulation of a mechatronic cleaning system for Type A barrels at La Paz Craft Brewery have demonstrated that it is possible to significantly improve cleaning efficiency, reduce water and chemical consumption, and enhance hygiene control. The project addressed existing deficiencies in hygiene, time efficiency, and resource consumption through the integration of mechanical, electronic, and control subsystems. The system successfully integrates mechanical design, automation, and control in a compact and adaptable structure.

All project objectives were achieved:

- The current system was analyzed and its inefficiencies quantified using the KCPE indicator.
- A mechanical design was developed to accommodate different barrel sizes, with structural integrity validated via FEA.
- A full control system was proposed using PLC and HMI integration, including detailed component selection.
- The new system demonstrated measurable performance improvements and operational safety.

The development of this project successfuly achieved the design of a mechatronic system addressing the specific needs of the brewery La Paz. Through a structured design methodology, the mechanical, electronic, and control components were carefully selected to ensure efficient operation while maintaining the required hygiene and safety standards. The system integrates automation techniques to optimize the cleaning process, reducing manual labor and improving consistency in the results.

The design was based on a detailed analysis of the cleaning needs and the integration of appropriate technologies to ensure efficiency. A SIEMENS S7-1200 PLC is used to control the existing variables with a control setting. The fact of obtaining a stainless steel structure not only provides strength and durability, but also reflects an economic adjustment to the brewery, recognizing that it is a widely used material in the brewing industry due to its number of applications and properties. A key aspect of the design was in the incorporation of a pneumatic piston to secure the barrel in place, ensuring stability during the cleaning cycle.

The proposed system:

- Reduced cleaning time by approximately 43%.

- Improved KCPE efficiency from 5.67% to over 83%.

- Lowered water and chemical usage by more than 35%.

- Increased operator safety and reduced physical workload.

All the initial objectives were successfully met:

- The existing system was analyzed and benchmarked using a standardized performance indicator.

- A mechanical and control design was developed and validated.

- Simulations confirmed the system's robustness and efficiency gains.

Although this study focuses exclusively on the design phase, the results provide a strong foundation for future implementations. Future work may include the construction and physical testing of the prototype, further optimization of energy consumption, and integration of IoT technologies for remote monitoring and predictive maintenance.

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