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A CASE-STUDY VISION

Design and implementation of a fuzzy temperature control for a craft beer production microplant using PLC

Diseño e implementación de un control difuso de temperatura para microplanta de cocción de cerveza artesanal mediante PLC

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ABSTRACT

In this study, a fuzzy-based PLC temperature control system was designed and implemented on a craft beer production plant. At present, the temperature-related controls of small-scale plants in Colombia are based on on/off models, which are not very stable in the preparation of craft beer, which generates significant changes in flavor, scent and texture. Therefore, it is intended to incorporate into the craft beer industry, solutions that guarantee repeatability, minimize costs and potentiate production, for this, a three-stage fuzzy control model is carried out: design, implementation and start up; This is how a study of the plant´s dynamics is carried out, the response is determined from the data, a fuzzy controller is designed by using Matlab software, and a graphical interface in LabView for data capture and storage. The controller demonstrates stability in relation to the temperature variable, which provides repeatability and significant energy savings.

Finally, it is concluded that the controller proved to be robust against major disturbances and stable at different temperatures, being a useful tool for efficiently controlling the variable.

RESUMEN

En este estudio se diseñó e implementó un sistema de control difuso de temperatura basado en PLC sobre una planta de cocción de cerveza artesanal. En la actualidad los controles relacionados a temperatura de las plantas a baja escala en Colombia se basan en modelos on/off, que son poco estables en la preparación de la cerveza artesanal, lo que genera modificaciones significativas en el sabor, el aroma y la textura. Por tanto, se pretende incorporar en la industria de cerveza artesanal, soluciones que garanticen repetibilidad, minimicen los costos y potencialicen la producción, para ello, se realiza un modelo de control difuso en tres etapas: diseño, implementación y puesta en marcha; se realiza un estudio de la dinámica de la planta. A partir de los datos se determina la respuesta, se diseña un controlador difuso mediante software Matlab, y una interfaz gráfica en LabView para captura y almacenamiento de datos. El controlador demostró estabilidad en relación a la variable, lo que proporciona repetibilidad y un ahorro energético significativo.

Finalmente se concluye que el controlador demostró ser robusto ante grandes perturbaciones y estable ante diferentes temperaturas siendo una herramienta útil para controlar de manera eficiente esta variable.

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1. Introduction

Automation provides solutions to different contexts such as: industry, agriculture, medicine, autonomy generation and efficiency. The craft beer industry is a relatively young process where characteristics must be improved since they depend on multiple variables, in general, they demand the implementation of control on the systems.

During the process of craft beer manufacturing, it is important to keep the temperature stable, a variable of interest to guarantee organoleptic differences in the recipes. Currently, most of controls related to temperature of low- scale craft beer produced in Colombia are performed by using on/off models that show low stability when preparing beer, thus generating unlikely repeatable recipes, which means that flavors, scents and textures of the product are modified.

Craft beer production is divided into three phases: grinding, production, fermentation. The production phase, in turn, is divided into four sub-stages: maceration, filtering, boiling and cooling. This craft beer elaboration process requires the implementation of control systems with great temperature stability to ensure that other variables immersed in the production process such as pH and liquid density keep in the desired parameters, thus ensuring a standard of quality and taste.

Automatic control systems have always looked for the ways to emulate human reasoning [1]. Classic control techniques base their design methodology on the information collected from the behavior of the production plant, generally in the form of an analytic model [2]. Plants that have special conditions, such as internal parameters with variations in regard to time or non-linear, have results that require more complexity due to the fact that information is not completely predictable or requires a high level of systematization [2], [3].

Fuzzy logic that can store experience in linguistic form of human inference about the solution of a problem has been incorporated into systems and devices of daily use such as appliances, video cameras, cell phones and even transport systems, [1], [2], [4]. Currently, controller manufacturers have introduced hardware and software that facilitate the implementation of control strategies such as fuzzy, which minimizes programming time and facilitates debugging in visual environments of intuitive development. Additionally, these visual environments facilitate integration with other specialized software such as Matlab and LabVIEW which allow online verification and migration from theoretical to practical development [5], [6].

Fermentation processes play a very important economic role in the food and beverage sector. To guarantee high quality, efficiency and in many cases repeatability, intelligent control strategies must be implemented [7]. Some temperature control projects have focused on improving precision during the fermentation process. Kuriakose et al. proposes a precision temperature controller by using Simulink from Matlab in conjunction with the Arduino development board [8]. Within the same phase of beer production, Connor et al. proposes a diffuse control applied to the fermentation process, compares it with the conventional PID, and obtains a clear alternative solution to be included in a beer manufacturing process [9]. Projects such as Babatunde's have also implemented a particular type of controller to improve process precision, using a Fuzzy Logic Controller (FLC) to regulate temperature, oxygen content and flow speed, where the first variable plays an important role in optimizing the fermentation process, Babatunde uses the Matlab fuzzy control toolbox [10].

Two works by the same author present in the first place a review of the typology of automatic control in breweries and controllers at an industrial level where PID type loop are included, the contribution is significant since cases of control applied to this segment of industry are identified and other implemented cases are studied [11]. Second, work on other phases of the beer production process, optimization and control of a filtration process is developed. Previous studies had identified that both the dynamics and the gain of steady state change, therefore, the multiple linear models are addressed. It also proposes to use a PID controller design technique based on two frequency response data points. Closed-loop control simulations that mimic the filtration process have been used to demonstrate the feasibility of maintaining the desired operating conditions of the filtration process by manipulating the system input [12]. On the other hand, Catalan proposes the creation of a semi-automated system for beer production, with a graphical interface to guide the user through the entire procedure, allowing him to know the temperatures in real time, control the actuators and ultimately, simplify the way of brewing beer [13].

This project aims to incorporate a solution into the craft beer production industry which minimizes costs and improves production through the design and implementation of a fuzzy automatic control system by using PLC which may enable the temperature variable to be monitored during the craft beer production process; the project is based on a real case study with application in the Colombian company Equipos Insumos Cerveza.

The project is divided into the following stages: i) previous studies where literature is reviewed and production plant and process are identified, ii) characterization stage where the dynamic behavior of the production plant is studied iii) design stage where the fuzzy controller is made based on the production plant behavior and the experts´ knowledge, and finally, iv) system´s implementation and start up.

2. Description of the production plant and process

2.1. Description of the craft beer production plant

The all in one production plant shown in Figure 1 developed by the Colombian company Equipos Insumos Cerveza SAS, is a proposal to minimize space and facilitate the craft brewing process in the four phases; maceration, filtering, boiling and cooling of the production stage, only in one equipment.

Figure 1. All in one craft beer production plant.

Source: own.

This production plant is an electrical equipment that incorporates several elements such as resistances to heat and boil the malt with water, a main pot for maceration and boiling, a basket to filter the grains contained in it, a wort recirculation pump, a winch to extract the basket containing grains, a cooler plate, a PT100 sensor, a temperature evaluation unit, a control panel with wired/wireless connectivity to a PC, a graphical interface from which temperatures and operating times for each processes can be adjusted, a Logic Controller Programmable PLC and finally, a solid state relay.

2.2. Description of the craft beer production process

The craft beer production process is made of three (3) stages defined as follows: grinding, production and fermentation. This research worked the production stage which is divided into four phases: maceration, filtering, boiling and cooling.

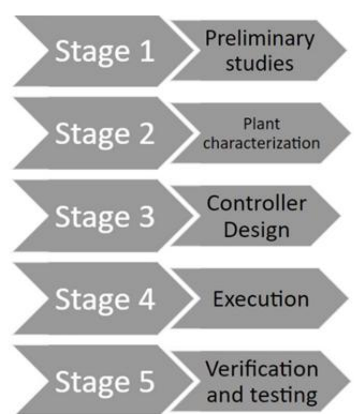
Grinding is the process where the enzymes contained in the malts convert starch into fermentable sugar. They determine the alcohol percentage that the craft beer will have [4]. The enzymes are activated and deactivated according to the temperature and time that the brewer stablishes [5].

Filtering is the process in which the wort is separated from the solid part of the cereals. Here, the grains are spayed with water for better extraction of residual sugars contained in the malt husks.

In the boiling process, volatile products generated during the craft beer production are eliminated. Additionally, in this process, the necessary density is obtained by evaporating the water. Besides, the desired hop elements such as bitterness, scent and flavor are extracted. Boiling must be strong to ensure the evaporation of harmful enzymes that may affect the quality of the wort. Finally, during cooling, the temperature of the wort is lowered to 25 °C through the cooler plate until an ideal temperature is reached to inoculate yeast and start the fermentation process.

3. Methodology

Figure 2. Project Stages.



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The project has the character of an applied field research; it is based on a real case study with application to the Colombian company Equipos, Insumos Cerveza which belongs to the craft beer production sector. It is performed in five stages as can be seen in Figure 2: preliminary studies, characterization, design, execution, testing and functional verification.

3.1. Preliminary Studies

A review was conducted in databases of indexed journals, information from the company and the industry. The information is classified, both from the state of the art and bibliographic references. The information provided by the company allows to describe the process, also participates actively in the production process of a recipe from production to presentation to the final consumer, the way in which the brewer must set up and operate the production plant by means of manuals is identified.

3.2. Production plant characterization

The characterization is carried out in open loop the pot temperature with water is raised to the maximum boiling point, and data collected from the process is stored by LabVIEW. Tests are running at different temperatures by applying various voltages to the heating actuator in order to better understand the dynamic behavior of the production plant.

3.3. Controller Design

Different control strategies were designed by using the FUZZY toolbox of Matlab once the dynamic of the plant production was understood. These strategies allow simple and quick modifications of the membership functions and the rules as well as to simulate the controller. Different input configurations such as the error, temperature reference, the derivative of the error and the integral of the error were considered in this design.

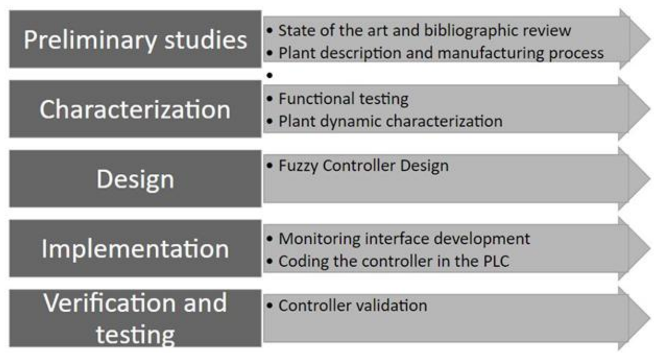
3.4. Execution

A graphical interface is developed in LabVIEW, the temperatures and times are configured in different phases of the production process, such as: turning the recirculation pump on/off, pausing the time, viewing the current temperature, viewing in graphs the history of the behavior of the temperature from the start of production, and at last, store the temperatures vs. time data in Excel. The fuzzy controller coding in the PLC was developed by combining different programming languages like ladder and structured text.

3.5. Verification and Tests

To validate, it was necessary that the design of the FUZZY controller and the codification of the controller in the PLC were developed reciprocally (Figure 3). Once the controller´s behavior was successful, a test consisting of the brewing of an English Bitter style craft beer was scheduled.

Figure 3. Sub-stages of the controller design methodology.



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4. Design of the Fuzzy controller

During the design of the controller, it was necessary to characterize the production plant to know the dynamic behavior and, in this way, adjust the membership functions of the fuzzy controller. This characterization was done in open loop by using water to simulate the wort. The temperature of the liquid contained in the maceration pot was raised to the maximum boiling point and the data was stored in a program developed for this purpose in LabVIEW. This characterization yielded important data such as the time required to increase a degree centigrade to the boiling point as well as the power required in the heating resistance to maintain different temperature points, Table 1.

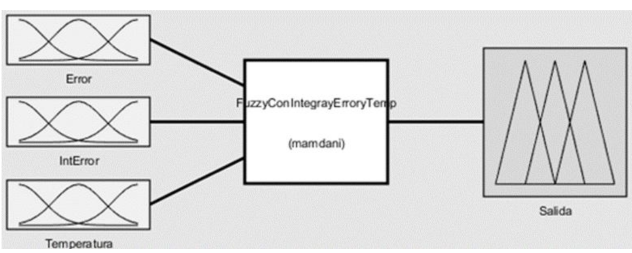
Three input variables named: “Error”, “IntError” and “Temperature” were created. The variable “Error” is in charge of keeping the error between the reference and the value of the controlled variable as close to zero as possible. The universe of discourse of this variable was established between [-100, 100] since the maximum error that may be generated does not exceed these limits due to the fact that none of the production processes require overheating the wort above 100 °C. The "IntError" variable keeps the steady-state error near the reference value. The "Temperature" variable, allows the controller to know the reference in which Figure 4 must arrive.

Table 1. Temperature values results.

Initial Temperature	20,3 °C
Final temperature	91,6 °C
Room Temperature	18 °C
Required Time to reach maximum temperature:	2 hours 10 min
Temperature rise per minute	0.54 °C approx.

Source: own.

Figure 4. Input and output variables of the Fuzzy controller.



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The output variable called "Salida" contains the membership functions corresponding to the different operating powers of the heating resistance approximated in the characterization of the plant. The inference method used was Mamdani and the number of fuzzy rulers was 20, The fuzzy design was developed in Matlab. Once the rules are defined, the response surfaces of the controller are evaluated (Figure 5) and it is observed that it responds aggressively when the error crosses the optimal operating window [-0.5 to 0.5] since the process is gaining or losing temperature quickly (disturbance) and requires an immediate response that eliminates this behavior.

As long as the error is in the optimal window of operation, the integral of the error takes action on the process in order to maintain a steady-state error close to zero (Figure 6). This error window is defined in the membership functions between [-0.5 to 0.5] guaranteeing that the system remains very close to the reference.

Figure 5. Temperature vs Error surface.

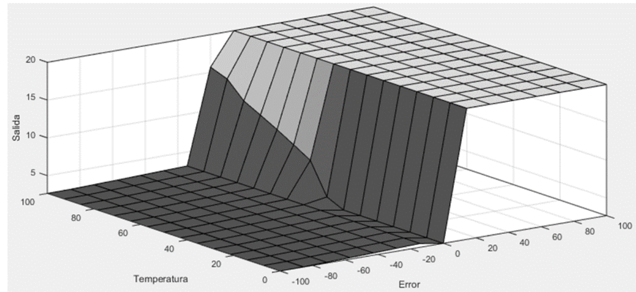

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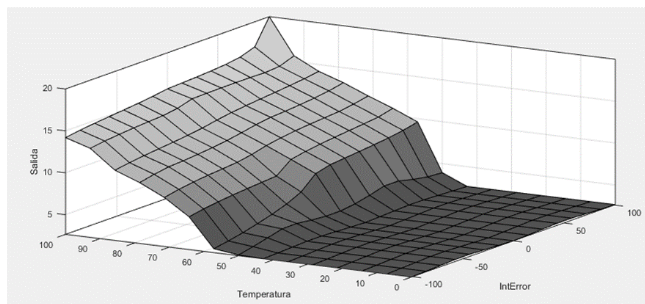
Figure 6. Temperature Surface Vs Integral Error.



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For all temperatures equal to or below 40 °C, the controller response is zero since these temperatures are not used in the cooking process. Therefore, the controller can be designed from 60 °C onwards, where these temperatures are used according to the type of beer to be brewed.

The Fuzzy controller designed in Matlab was implemented in the Siemens S7-1200 PLC by using the TIA PORTAL V14 programming environment. The "Totally Integrated Automation" allows programming in Instruction List (IL), Structured Text (ST), Ladder Diagram (LAD) and Function Block Diagram (FBD) under the IEC 61131-3 standard.

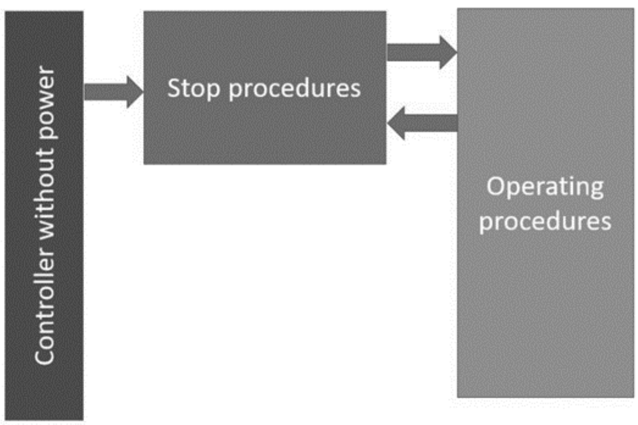
The methodology used in the design algorithm (Figure 7) was inspired by the GEMMA guide, which has defined stages of the process as follows:

- **Control without power:** When the PLC is disconnected or in STOP mode and enters the RUN state, it loads the initial starting conditions in the memory and in the variables that the process requires prior programming by the designer.

·Process in stop: It assumes the null output of all the outputs of the PLC. The system is idle and ready for to start.

·Process in operation: It is the state in which the machine normally produces, which means that it does the task for which it was conceived, it is the most important state since it is the production state.

Figure 7. Block diagram of the design in the PLC.



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5. Results

The design specifications required by the company are shown in Table 2.

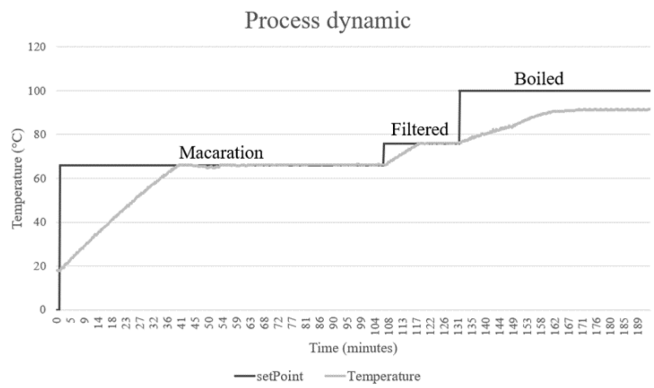
Table 2. Design specifications.

Design specifications requested by the company			
Specifications	**Minimum**	**Nominal**	**Maximum**
Steady state error	-0.5 °C of reference value	Equal to reference	+0.5 °C of reference value
Ambient temperature rise time to 100 °C (minutes)	80	90	120
On impulse °C	0	0	0.5

Source: own.

The complete process dynamics is shown in Figure 8. Here, it is observed how the fuzzy controller meets the required design specifications. During the mashing process, the controller maintains a steady state error of ± 0.2 ° C, which is within the operating limits determined in the design specifications at ± 0.5 ° C.

Figure 8. Dynamics of the process.



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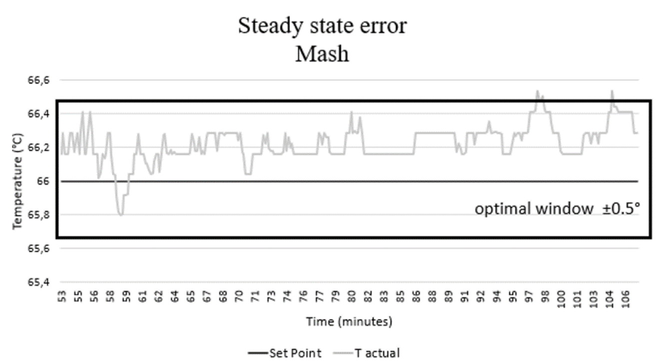
The temperature peaks shown in Figures 9 and 10 correspond to rapid temperature transitions which are detected by the sensor and read as noise due to the sensitivity.

Figure 9. Steady state error during maceration.



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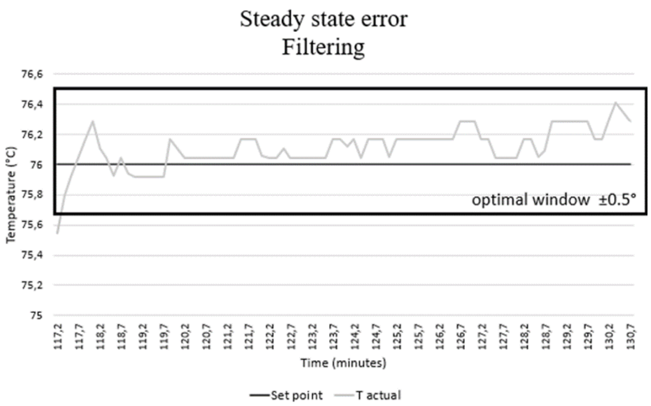
During the filtration process, the controller maintains a steady-state error of ± 0.1 ° C which is within the operating limits determined in the design specifications (Figure 10).

Figure 10. Steady state error in the filtration process.



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When the filtration time ends, the final boiling process begins. For this process, the system sets automatically a new reference of 100ºC. As the experiment was carried out in Bogotá D.C. (2600 masl), the system only reaches 91.6 °C (boiling point) due to atmospheric pressure. The error in the steady state is ± 8.4 °C, however, this error is not critical because the boiling point in the city is lower (Figure 11).

The energy consumption throughout the craft beer cooking process was recorded in a biphasic energy meter of the brand Hiking. Data were taken at the beginning and at the end of the process, obtaining the results displayed in the: Table 3. This information was compared with the energy consumption of another plant with similar characteristics with an ON/OFF control system.

Figure 11. Boiling temperature behavior.

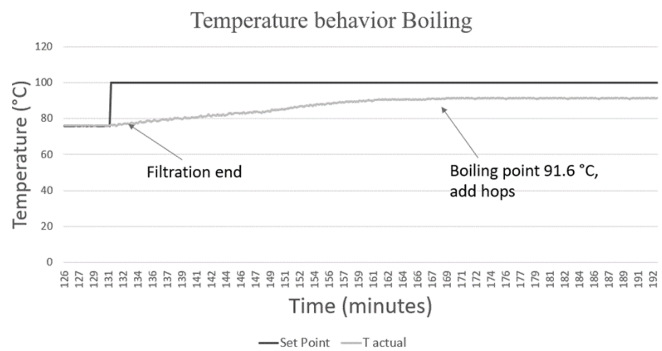

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Table 3 shows that the energy consumption of the all-in-one plant is approximately 340 Wh lower than that of the plant with similar characteristics. This means that the fuzzy control makes better management of electricity consumption by applying constant power and low magnitude to the resistance in most of the cooking process, unlike the ON / OFF control system that varies the power of the resistance continuously between 0 W and 3 kW.

Table 3. Electric consumption data taken from the electric energy meter.

Plant	Energy consumption kWh	Electric power cost ($/kWh)	Cooking energy cost ($)	Production (liters / month)	Energy cost per liter ($ / liters)
On/Off Control	11,4	$ 495	$ 5.643	2.100	$ 169.290
Fuzzy Control (all in one)	10,31	$ 495	$ 5.103	2.100	$ 153.104

Source: own.

6. Conclusions

A fuzzy control model was designed, implemented and tested from the use of a programmable logic controller, on a craft beer brewing plant, the system proved to have low uncertainty and great stability against external disturbances associated with the temperature.

The conventional control generates large errors during cooking, which causes organoleptic inaccuracies. Therefore, the implemented fuzzy control model makes the process repeatable while the robust control of the system guarantees identical flavors, aromas and textures in the same recipe during its performance.

The temperature fuzzy control model makes the system more efficient during the extraction of sugars, since it provides great stability in the variable, especially at the reference points in which the proteins are activated. In consequence, the malts required for the processing are reduced and hence the cost of production.

During the tests, the comparison of the conventional plant with the plant that involves the control model is carried out. An energy saving for the producer during the elaboration was observed in the second one, which may mean accordingly, a significant cost reduction.

In future research, it would be important to generate a comparative study using fuzzy control in plants with alternative energy sources. Likewise, the need to implement variables supervision and monitoring systems, graphic interfaces that allow rigorous visualization and control of multiple parameters is seen.

It is important to reproduce this type of controllers using low-cost technology with the aim to facilitate the technification of the production in the craft beer industry and guarantee competitiveness in the markets.

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