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Development of pilot plants for engineering education

Desenvolvimento de planta piloto para o ensino de engenharia

Desarrollo de una planta piloto para la enseñanza de ingeniería

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Abstract
The rapid changes in social interactions and the easy access to information brought by technological advances require that professors rethink and rebuild teaching to maintain its quality. Active methodologies have been used to ensure the development of essential skills in professionals to deal with the current challenges and demands of the job market. This study presents the use of active project-based methodologies with undergraduate and postgraduate engineering students at the Federal University of Minas Gerais. This study aims to report on the implementation of a pilot plant for the causticizing stage of the pulp and paper Kraft Process and the development of two prototypes of industrial sludge drying equipment using solar energy and to evaluate the impact of the activities on the professional training of the people involved and the development of skills and competencies expected of engineering professionals according to the National Curriculum Guidelines, such as the ability to work in teams. The students could apply their technical knowledge in real situations in an interdisciplinary and multidisciplinary collaborative environment that encourages the resolution of complex engineering problems innovatively, with a holistic and humanistic vision that also considers social and sustainable aspects. They also demonstrated increased motivation and experienced the connection between industry and academia, which is essential to demonstrate the applicability of the techniques learned during the courses.
Keywords: Pilot plant; Teaching; Engineering; Active methodology; PjBL.

Resumo
As rápidas mudanças nas interações sociais e a facilidade de acesso à informação trazidas pelo avanço da tecnologia exigem que os docentes repensem e modifiquem a forma de ensino de modo a garantir sua qualidade. Metodologias ativas de ensino têm sido usadas para assegurar o desenvolvimento de competências essenciais aos profissionais, para que consigam lidar com os desafios e as demandas atuais do mercado de trabalho. Este trabalho apresenta o emprego de metodologias ativas baseadas em projetos com alunos da graduação e da pós-graduação na área de Engenharia na Universidade Federal de Minas Gerais. O objetivo deste estudo é relatar a implementação de uma planta piloto para a etapa de caustificação do Processo Kraft de papel e celulose e o desenvolvimento de dois protótipos de equipamentos de secagem do lodo industrial com uso de energia solar e avaliar o impacto das atividades na formação profissional das

pessoas envolvidas e no desenvolvimento de habilidades e competências esperadas de profissionais da engenharia segundo as Diretrizes Curriculares Nacionais, como por exemplo a capacidade de trabalho em equipe. Os discentes foram capazes de aplicar o conhecimento técnico em situações reais, em um ambiente de colaboração interdisciplinar e multidisciplinar que fomenta a resolução de problemas complexos da engenharia de forma inovadora, com um viés holístico e humanista que considera também aspectos sociais e de sustentabilidade. Também demonstraram maior motivação e, além disso, vivenciaram a conexão da indústria com o meio acadêmico, essencial para demonstrar a aplicabilidade das técnicas aprendidas ao longo dos cursos.
Palavras-chave: Planta piloto; Ensino; Engenharia; Metodologia ativa; PjBL.

Resumen
Los rápidos cambios en las interacciones sociales y la facilidad de acceso a la información propiciada por el avance de la tecnología requieren que los docentes repiensen y modifiquen la forma en que enseñan para garantizar su calidad. Se han utilizado metodologías docentes activas para asegurar el desarrollo de habilidades esenciales en los profesionales, para que puedan afrontar los retos y exigencias actuales del mercado laboral. Este trabajo presenta el uso de metodologías activas basadas en proyectos con estudiantes de pregrado y posgrado en el área de Ingeniería de la Universidad Federal de Minas Gerais. El objetivo de este estudio es informar sobre la puesta en marcha de una planta piloto para la etapa de caustificación del Proceso Kraft de pasta y papel y el desarrollo de dos prototipos de equipos de secado de lodos industriales mediante energía solar, así como evaluar el impacto de las actividades en la formación profesional de las personas implicadas y en el desarrollo de las habilidades y competencias esperadas de los profesionales de la ingeniería según las Directrices Curriculares Nacionales, como la capacidad de trabajar en equipo.. Los estudiantes pudieron aplicar conocimientos técnicos en situaciones reales, en un ambiente de colaboración interdisciplinaria y multidisciplinaria que fomenta la resolución de problemas complejos de ingeniería de manera innovadora, con un sesgo holístico y humanista que también considera aspectos sociales y de sostenibilidad. También demostraron una mayor motivación y, además, vivieron la conexión entre la industria y la academia, fundamental para demostrar la aplicabilidad de las técnicas aprendidas a lo largo de los cursos.
Palabras clave: Planta piloto; Enseñanza; Ingeniería; Metodología activa; PjBL.

1. Introduction

With the internet and technology advances, society is daily bombarded with new means of communication and social interaction. People want to participate in the fast and innovative climb the fourth industrial revolution provides while traditional media becomes obsolete. Access to information is just a click away, and given this speed, teachers are finding it challenging to keep students' attention. The famous blackboard with hand drawings, a traditional tool, often fails to satisfy the student's desire to learn. Thus, the discussion of learning methodologies that are active and adapt classroom didactics to the reality of the new generation is essential for quality education (Kapranos, 2013; Felder, 1988; Sukacke et al., 2022; Santos et al., 2021).

In higher education, where students have to work in addition to their educational obligations, the discussion of making the classroom environment more collaborative and attractive to students is essential. Traditional courses such as engineering have historically been marked by theoretical classes that exhaustively discuss topics without any practical content experience (Belisário et al., 2020). In today's society, there is, therefore, a mismatch between what is demanded - multidisciplinary and proactive professionals - and what the university actually provides - professionals who are not very engaged with the multidisciplinarity required for today's challenges.

In this way, using tools that allow students to experience the problems required by the market, such as pilot plants, is of great value to higher education (Ahmed & Esmail, 2019; Ortiz, 2019; Vega & Navarrete, 2018). These environments, which simulate the operation of large industrial processes, are part of a project-based learning (PjBL) methodology since learning is focused on constructing interdisciplinary and team projects (Sukacke et al., 2022). The aim of this paper is, therefore, to present the application of active methodology in engineering teaching through the implementation of projects to develop prototypes of equipment and pilot plants with the participation of students from the Federal University of Minas Gerais in order to reproduce the manufacturing scenario of a pulp mill.

2. The Use of Active Methodologies in Engineering Education

Among the various active learning methodologies in a growing trend in academia, problem-based learning (PBL), PjBL, and challenge-based learning (CBL) stand out. PBL projects focus on developing students' problem-solving skills - whether fictitious or not (Sukacke et al., 2022). In other words, PBL projects start from a problem presented by the mentor/teacher, and all the students' work and action plan are geared towards solving this problem, always with a focus on generating technical knowledge for the student (Sukacke et al., 2022; Noordin et al., 2011).

On the other hand, PjBL projects are more robust, and sometimes authors state that when implementing a PjBL, there will indirectly be typical PBL activities (Sukacke et al., 2022; Noordin et al., 2011). PjBL projects have emerged as one of the most relevant and studied strategies for improving learning in engineering schools because they are centered on using technical knowledge to solve real problems (Sukacke et al., 2022).

Finally, CBL projects, despite sharing similarities with PBL and PjBL, go further, as the challenge is not entirely predefined. In this type of project, students and community members participate in formulating the intervention to be worked on, but the teacher only facilitates and accompanies the learning. CBL has a multidisciplinary approach that encourages students to develop solutions to real problems with the support of technology. In addition, CBL challenges are expected to promote innovative, creative interventions that stimulate the formulation of relevant problems and issues through the investigation of compelling questions and reflection on the learning and impact of the actions chosen by the students (Sukacke et al., 2022).

In this learning bias in which students actively participate during their training, the implementation of projects using pilot plants is an excellent ally in the academic and technical training of professionals. These collaborative spaces offer an integration and connection between industry and academia, which, according to Vega and Navarrete (2018), is a crucial opportunity for success in engineering education. In addition, these environments simulate the operation of large industrial processes. They are inserted in the context of PjBL-type methodology since learning is focused on the construction of interdisciplinary and team projects (Sukacke et al., 2022).

In the context of the Chemical Engineering course, in which the professional is responsible for controlling and operating industrial processes, operating systems that are similar to the real thing is the best form of training in engineering control (Ahmed; Esmail, 2019). Nevertheless, the use of a pilot plant gives students a feeling of greater proximity to the experiences of the job market and industry and allows them to visualize different physical, chemical, and thermodynamic phenomena discussed throughout their degree (Ortiz, 2019).

Ortiz's (2019) report from the Department of Chemical and Environmental Engineering School of Engineering (ETSI) at the University of Seville/Spain concludes that the students who took part in the laboratory experience in a pilot plant were more motivated during the project. In addition, the students demonstrated better teamwork skills and a greater understanding of subjects related to specific professional practice (Ortiz, 2019). Similar to these observed gains, Ahmed and Esmail (2019) report that the use of pilot plants in the context of chemical industries helps transfer knowledge and skills to those involved in the project. The gains for industry and universities are also numerous since bringing academia and the productive sector closer together aligns research and development efforts with social, environmental, and market demands (Vega & Navarrete, 2019).

The pulp industry is a growing market sector in Brazil, especially during and after the COVID-19 pandemic, due to the high demand for hygiene and personal protection materials (Industriall, n.d.). The pulp and paper sector is segmented into three types of industrial units: pulp extraction plants, paper plants, and integrated plants- which produce pulp and paper (Empresa de Pesquisa Energética —EPE, 2022).

The most widely used process for manufacturing cellulose pulp is Kraft, characterized by being a closed circuit with recovery of the inputs used in the manufacturing unit (Rodrigues, 2019). Despite the consolidation of this production process, industries still have to deal with certain difficulties, such as the use of lime of different qualities, which has an impact on production control, the quality of green liquor, and the control of causticizing efficiency (the stage of recovery of the white liquor input - sodium hydroxide - which provides a financial and environmental gain to the process) (Albeche, 2008). In addition, faced with the environmental issues experienced in recent years due to extreme climate change, industries are being questioned about their sustainable actions. In this way, the green aspect is growing in corporate circles, either by reducing the consumption of some input or fuel, or by handling and reusing waste. The Kraft process generates a large amount of solid waste, mainly sludge from the mill's effluent treatment plant (Gonçalves et al., 2023).

Faced with this reality experienced by the pulp and paper industry, a group of undergraduate students and two Ph.D. students, all in Engineering courses were asked to carry out prototype equipment projects (sludge dryers) and pilot plants (causticizing plant) to consolidate their learning. The projects were developed with the support of the advisors, always to encourage proactivity and multidisciplinarity among the students involved. In addition, the projects were conceived to bring the university closer to the industries, as well as collaborate in the development and study of the bottlenecks experienced by the pulp industry. Also, to study the management of industrial waste, one of the study's objectives through the development of prototypes is to dry the sludge, since this sludge can be reused for other purposes, such as generating energy.

The following sections present two examples of educational innovations using PjBL methodology and digital technologies in the classroom and laboratory. The first part shows the gains in training a group of undergraduates in Chemical Engineering when the advisor encouraged the use of multidisciplinarity in designing a pilot plant for the causticizing stage of the Kraft Process. The second part addresses the assembly of two prototype sludge dryers, the first to survey the sludge drying curves using air preheated by solar emission and the other in development that aims to increase the efficiency of the entire process based on the experiences with the previous prototype.

3. Methodology

A case study/report can be understood as collecting and recording data from an experience to organize the information, as well as analytically evaluating it and its effects/consequences for the environment and those involved (Mendonça, 2014). In the teaching context, this type of publication addresses a set of procedures related to the development or use of cases in the teaching context (Alberton & Silva, 2018).

The projects developed at the School of Engineering at the Federal University of Minas Gerais (UFMG) used active teaching methodologies as a tool for the academic and professional development of the students involved. Since the projects are innovative and it is difficult to find similar cases at the university, the case reports were presented as a way of following up the projects, as well as a tool for monitoring the impact on those involved in the project. In this way, this case report used as its methodological basis the guidelines proposed by Alberton & Silva (2018) for writing a case report for teaching. The structural elements that support the preparation of this study are presented below:

- **Introduction and Context of the Case:** delimiting the time and place in which the case takes place, as well as presenting the protagonists of the case and introducing the project;
- **Dilemma of the case:** presentation of specific information to provoke the reader to reflect on the decision involved;
- **Closing the case:** comprises one or two final paragraphs in which the author presents some guidelines on the case dilemma that announces its closure and the decisions that need to be made.
- **Teaching Notes:** presentation of the technical, academic, social, and professional skills developed by those involved in the cases analyzed.

4. Experience Report 1: Pilot Plant for the Causticizing stage of the Kraft Process

The Chemical Engineering degree course at UFMG has a subject called Operations and Processes Laboratory (LOP) in the ninth semester, equivalent to the Final Paper. By definition, the subject sets a group of students to develop a project autonomously, so that various chemical engineering concepts must go beyond theory and be applied in practice (Belisário et al., 2020).

Between August and December 2023, a group of four students began implementing a pilot plant in the Operations Laboratory (LabOP) for the causticizing stage of the Kraft Process. It is important to note that this report only covers one semester of the project and that students' participation in the operation and design of the Pilot Plant did not end in December 2023.

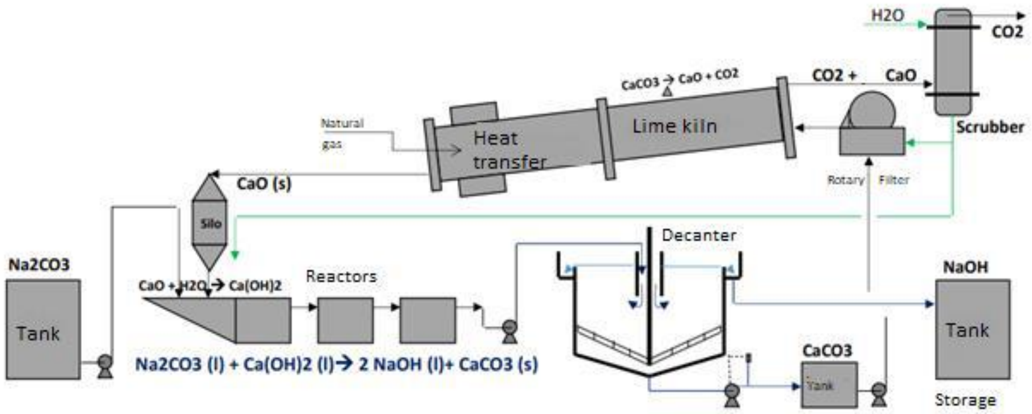
Initially, the students met with the project's advisors to discuss the theme and discover the problems to solve. In addition, a schedule of activities was drawn up, and the frequency of meetings between teachers and students to monitor activities was defined (synchronous means were used – in-person and virtual meetings and classes - and asynchronous means - like the WhatsApp messaging app).

The Kraft process consists of several stages: pulping, bleaching, evaporation, boilers, causticizing, and lime kiln. These stages are crucial to ensuring the efficiency and quality of the final product. Pulping, the first stage of the process, involves separating the fibers from the wood using alkaline liquor, as described by Kaur, Singh, Khatri and Arya (2020). Next, bleaching is carried out to remove impurities and improve the whiteness of the pulp, a fundamental process as detailed by Mboowa (2024). Evaporation is another crucial stage in which water is removed to concentrate the pulp, as evidenced by Biermann (1996). Boilers play an essential role in generating the steam needed for various process stages, as pointed out by Hammett (1994). As Sixta (2006) pointed out, causticizing is responsible for recovering chemical products and maintaining the right pH in the process. Finally, the lime kiln, as described by Chai, Hui, Fan, Kang and Song (2019), is used to produce lime, one of the essential components in the causticizing process. Together, these steps ensure the efficiency and sustainability of Kraft pulp production.

The various stages of the Kraft process in pulp production generate numerous wastes, including solid, liquid, and gaseous, constituting a significant environmental challenge. In recent years, there has been an increase in the study and development of ways to reuse this waste to avoid inappropriate disposal, such as depositing solid waste in landfills. The search for passive disposal alternatives has been an area of focus, as evidenced by various studies. For example, Kaur et al. (2020) discuss solid waste recovery in the pulp industry, highlighting recycling and reuse methods. Mboowa (2024) discusses using biological treatments for liquid waste to reduce the pollution load. In addition, Hammett (1994) highlights the importance of capturing and using waste gases in industry to minimize environmental impact. These approaches aim not only to mitigate the negative effects of the waste generated by the Kraft process but also to promote sustainability and efficiency in the pulp industry.

The causticizing stage of the Kraft Process (Figure 1), the target stage of the Pilot Plant project, is characterized by a series of agitated tanks that operate as reactors, a decantation and filtration system, and a calcination kiln. Given the diversity of the equipment, the students initially conducted a bibliographical review of the pulp and paper industry and the causticizing stage to learn about the essential parameters for the proper operation of the pilot plant.

Figure 1 - Representative illustration of the flow of equipment in the causticizing stage.

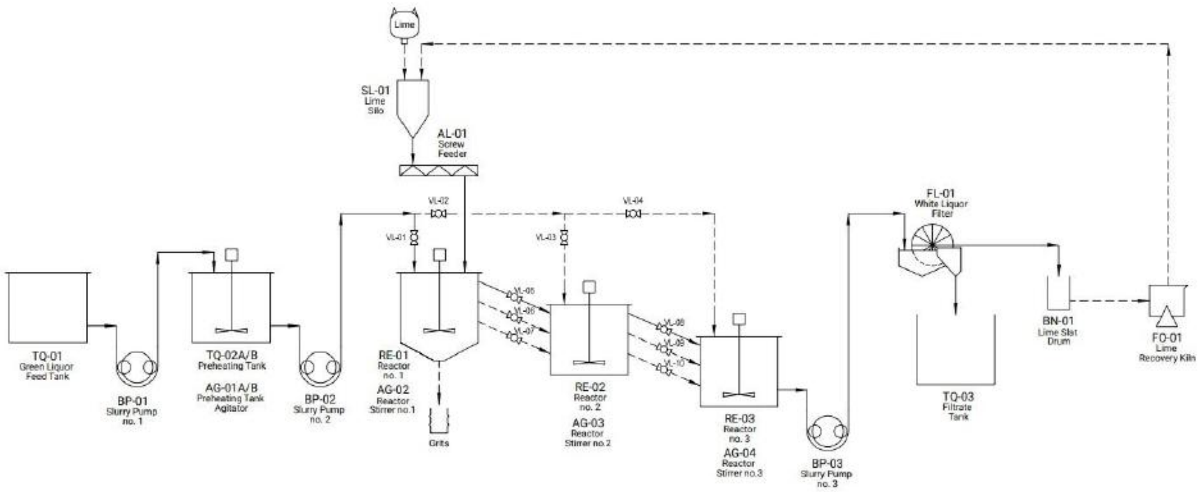


Source: Moraes et al. (2018).

The industrial process shown in Figure 1 aims to recover white liquor ($NaOH$ + Na_2S solution), which is responsible for pulping wood, from a solution of Na_2CO_3 and Na_2S. Note in Figure 1 that the Na_2CO_3 solution is pumped to the first causticizer, called the slaker, which receives an addition of lime (CaO). After the reaction between Na_2CO_3 and CaO is completed throughout the series of causticizers, $CaCO_3$ and $NaOH$ are obtained. The fluid passes through a decanter to separate the phases, and the $NaOH$ returns to the wood pulping stage. The $CaCO_3$ goes to a filter and is then calcined to produce lime.

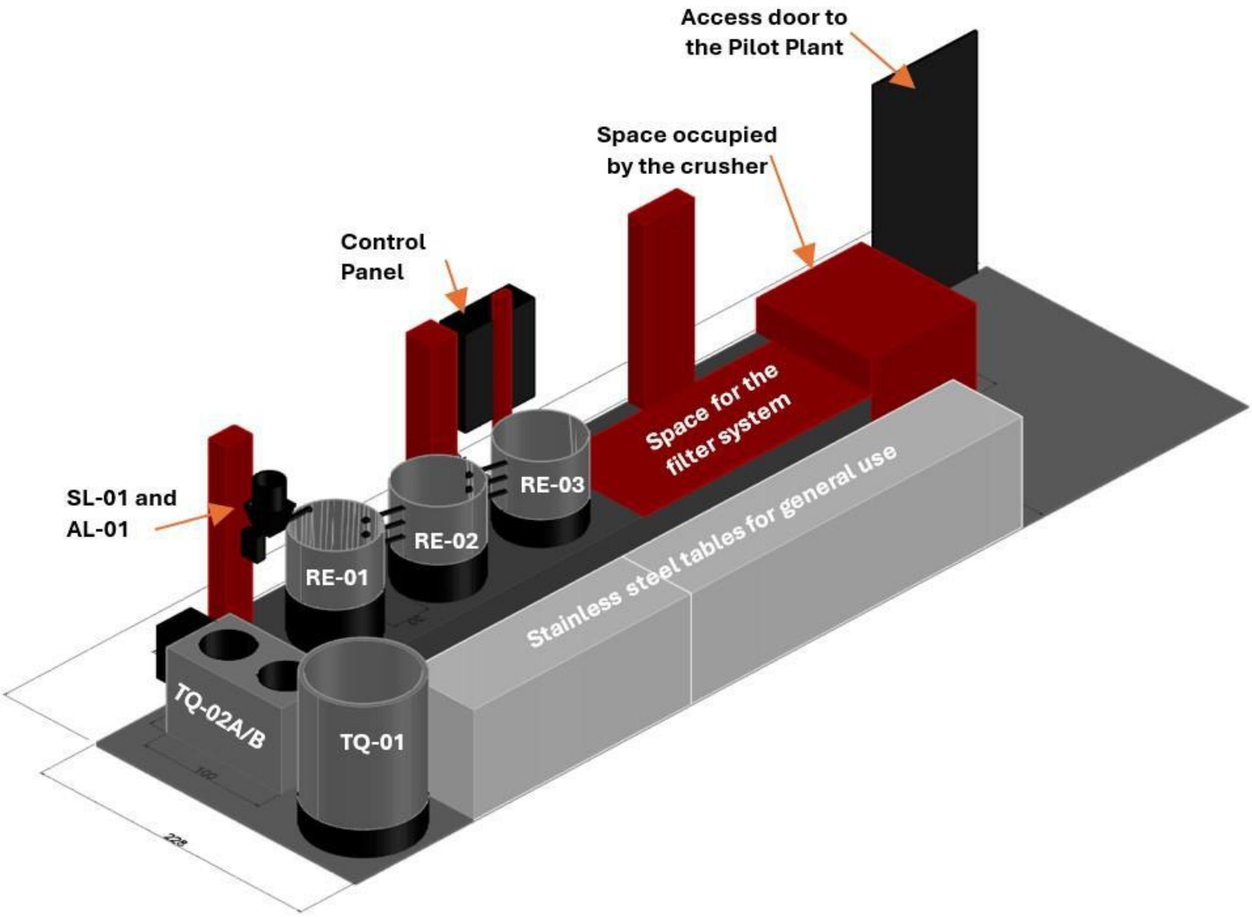
Subsequently, after reviewing the literature and visiting LabOP to get to know the physical space reserved for the pilot plant, as well as the equipment available for use in the laboratory, the students built the process flow diagram (PFD) (Figure 2) and the layout of the plant using the AutoCAD tool (Figure 3). This stage allowed them to apply and use the knowledge acquired in previous subjects, such as Technical Drawing, Fluid Mechanics, and Industrial Processes, and teach the students about ergonomics and process safety. During the layout construction stage, the students evaluated the effects of sedimentation in the pipes using the critical velocity calculation in MS Excel.

Figure 2 - Developed flowchart of the process.



Source: Authors.

Figure 1 - 3D Visualization of the developed layout (Rear Shading)[1].



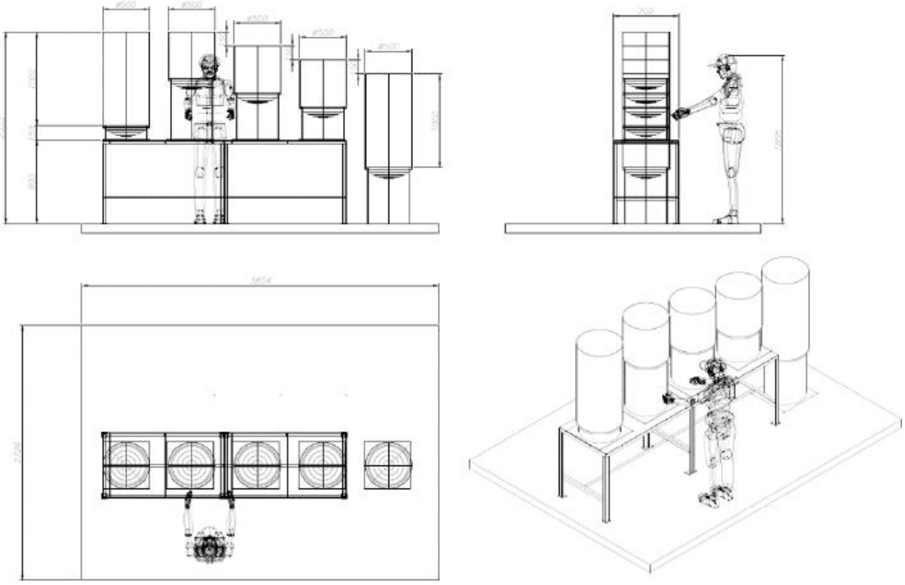
Source: Authors.

Figure 2 shows a similar equipment flow to Figure 1, except for the decanter. In the Pilot Plant project, the students incorporated a system for feeding and heating the Na_2CO_3 solution, given that the reaction has an ideal temperature of around 80°C. Figure 3 shows the three-dimensional view of the flowchart in Figure 2, except the filtering system, which will be designed in a later semester, and the calcination furnace - a muffle furnace available at LabOP will be used, which is not located in the Pilot Plant space. In addition, Figure 3 shows the control panel that will be used in the plant and the access route to the Pilot Plant space, which will be isolated from the rest of the LabOP by glass panels.

The project shows a careful approach to ergonomics, as seen in the layout of the elements shown in Figure 4. This approach seeks to ensure that the environment or product is adapted to the physical and cognitive characteristics of the user, promoting comfort and efficiency. This alignment with contemporary ergonomic principles is supported by authors such as Dul, Brucker, and Weerdmeester (2012), who highlight the importance of considering the interaction between human beings and the work environment when developing ergonomically effective projects as shown in Figure 4.

[1]. A jaw crusher will be kept on-site in the space reserved at LabOP for the Pilot Plant.

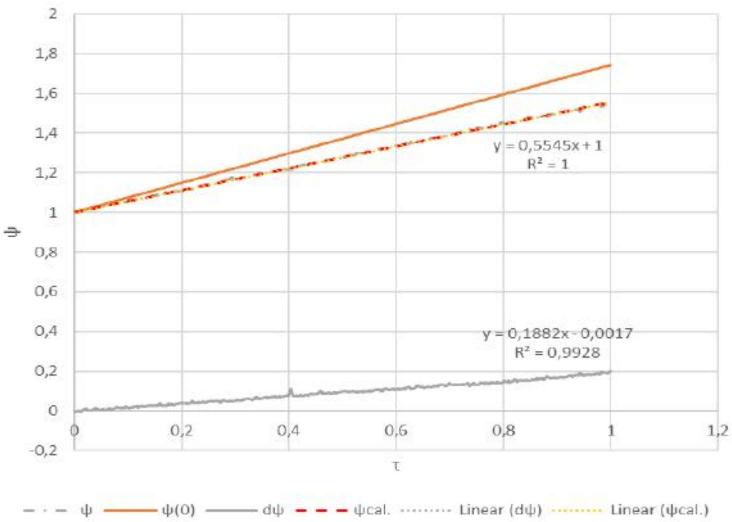
Figure 4 - Example of an ergonomic environment.



Source: Authors.

At the end of the project's first stage, the students installed a new electrical system in the heating tanks available in the LabOP, which had been unusable due to broken wires and connections. During this project phase, the students developed skills related to the safety of electrical systems and control devices such as relays, electrical harnesses, and thermostats. In addition, after installing the new electrical system, they tested the operation of the water heating tanks. Tank operating curves were obtained, and the agitation's effect on the fluid's temperature in the tank was analyzed. The collection of heating data made it possible to use numerical methods, specifically the Orthogonal Placement Method, to build models for simulating and extrapolating the heating system's operation (Figure 5).

Figure 5 - Adimensional temperature variation as a function of adimensional time

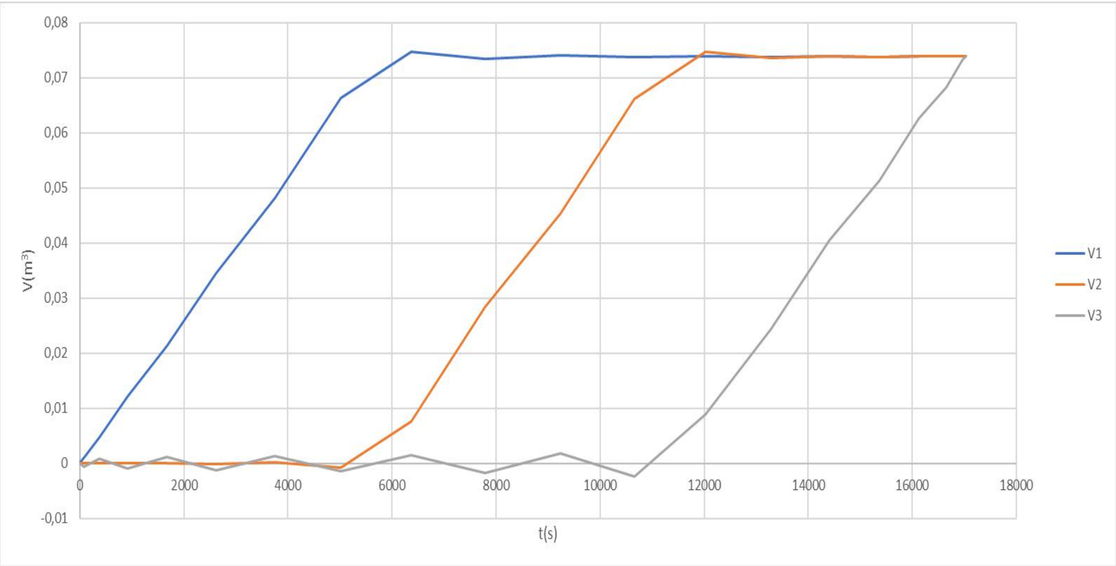


Source: Authors.

In Figure 5, the curve $\psi(0)$ represents the ideal heating, using the theoretical power of the heater and considering the system with an adiabatic boundary. However, the actual heating, represented by (ψ), shows an inefficiency in the insulation of the real system, generated by energy losses. In addition, Figure 5 shows the good prediction of the mathematical model when evaluating the $\psi\ cal.$ and ψ curves, which are practically overlapping. This stage with the heating tank allowed the consolidation of the knowledge provided in the Heat Transfer courses, as well as introducing the students to a numerical method that allows partial and ordinary equations to be solved using the MS Excel software.

Finally, tests were carried out on the pilot plant's pumping system using peristaltic pumps. For this system, the operation of three pumps with three tanks in series was modeled and simulated using MS Excel software (Figure 6). The curves shown in Figure 6 provide relevant information on the time required for the tanks to reach 80% of their maximum volume: tank 1 around 6000s (around 1.7h), tank 2 around 12000s (3.33h) and tank 3 around 17000s (4.72h). This behavior of the fluid volume variation is consistent with the system proposed in the pilot plant layout, and it is necessary to evaluate the pump's behavior with the use of green liquor as a fluid in the future.

Figure 6 - Variation in the volume of fluid in tanks 1, 2 and 3 as a function of time in seconds [2].



Source: Authors.

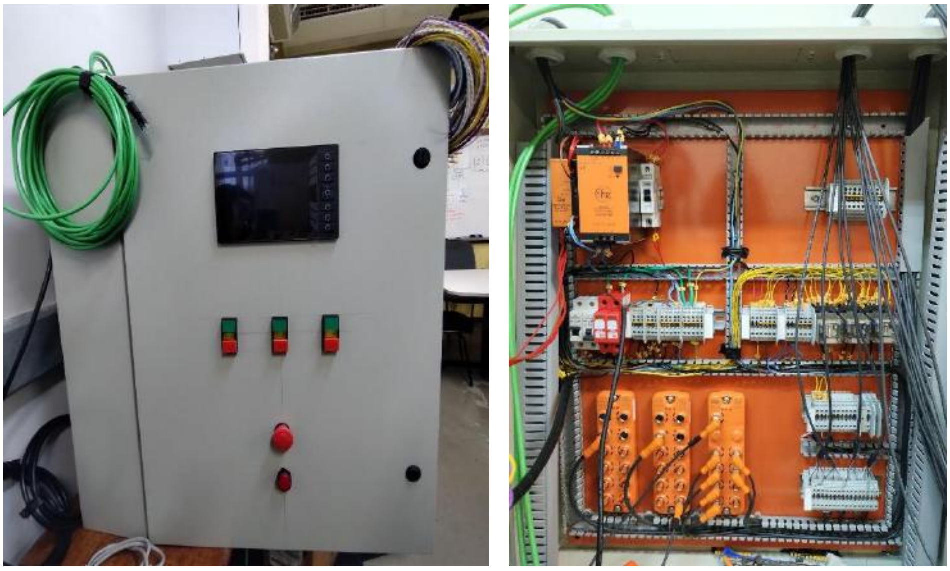
The results made it possible to validate the feed rate proposed by the undergraduates, as well as predict the operating time of the process using a buffer tank. Last but not least, the test highlighted the importance of studying pressure drop due to friction during fluid transportation, as well as consolidating the technical knowledge acquired in fluid mechanics.

As a final step, the students wrote a technical report presenting the literature review, methodology and all the steps taken during the semester. The work was argued before a panel of professors from different areas of the Chemical Engineering course, and discussions were held on technical issues that contributed to the project's scope.

It is worth noting that during the project's development, the students installed a control and automation panel for the pilot plant. In the future, this equipment will be used to read the plant's operating variables, such as flow, temperature and level, via the Human-Machine Interface (HMI) (Figure 7). The panel was developed with the Department of Electronic Engineering at UFMG.

[2] The modeling considers using around 80% of the tanks' capacity due to the predefined height of the pipes connecting the tanks and the safety procedures for operating the plant, given the alkaline environment in which the causticizing stage takes place.

Figure 7 - Control Panel: (a) front view; (b)inside view.



(a) (b)

Source: Authors.

In Figure 7a it can be seen that the Human Machine Interface (HMI) has been positioned in an ergonomic and easily accessible way, being fixed so that it is at a height of about 1.60m from the floor, after installation in the laboratory, allowing the main information to be at eye level (person of average height). This choice meant that the internal part had to be organized in such a way as to accommodate the device cables without hindering the other components used, as shown in Figure 7b.

Since LOP is a semester-long course, a new group of students will participate in the pilot plant development project with each new cycle of the academic calendar. Given this, the 2023/2 group not only carried out the steps described above but also listed subsequent tasks for the smooth running of the project, given their experience and discussions with the advisors.

5. Experience REPORT 2: Development of Prototype Dryers for Sludge Generated During the Kraft Process

Research related to drying industrial sludge has been part of the postgraduate program in Sanitation, Environment and Water Resources (SMARH) at the Federal University of Minas Gerais (UFMG) since 2020. This report includes a compilation of the experiences of two doctoral students in the project: one responsible for developing the first prototype and who played a large part in the development of the second, which entered the program in 2020, and the second responsible for implementing the second, which entered in 2023.

The students hold weekly meetings with all the research group members (professors, researchers from other institutions, doctoral and master's students). During the meetings, the members make presentations to monitor the activities (synchronous virtual meetings and constant information exchanges via WhatsApp messages are used).

The doctoral students visited two Wastewater Treatment Plants (WWTPs) for the project. The first was a steel drawing plant to understand the generation of industrial sludge. The second was to a pulp mill in north-eastern Brazil to establish a partnership and understand all the stages of sludge generation. In addition, on this second visit, the students followed the process on the control panels and on-site, identifying the points where samples were taken for analysis and the disposal of industrial sludge. Meetings with plant engineers occur whenever necessary (synchronous virtual meetings and exchanges of information via WhatsApp messages are used).

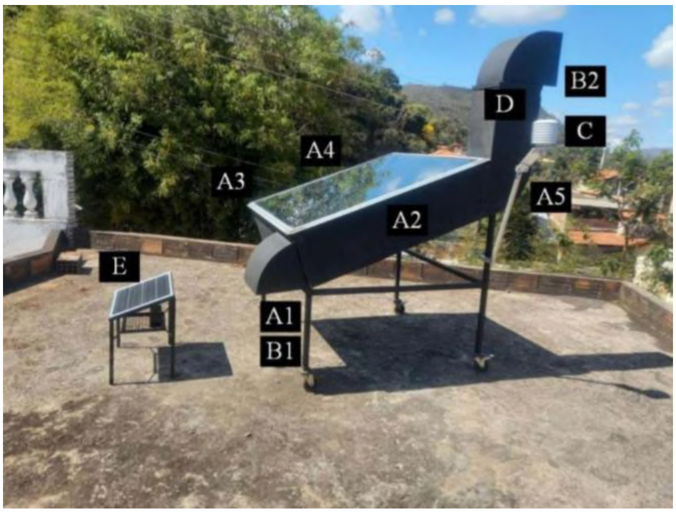
As previously reported, all the stages of the process generate waste, and one of the main ones is the sludge from the WWTP. So, another objective of the work was to develop new prototypes of equipment for drying industrial sludge, which is the first stage for reusing this input in the production process.

Drying is often considered the first crucial stage in reusing and recovering industrial sludge generated in industrial processes, including in the pulp industry. This process is essential for reducing sludge volume and facilitating its handling and transportation. Recent studies have highlighted the importance of drying as a fundamental initial stage for recovering energy from industrial sludge. Kim et al. (2022) discuss thermal drying as an effective approach for reducing the sludge's moisture content and preparing it for subsequent recovery processes. In addition, Vieira et al. (2021) explore the use of drying techniques to produce biosolids with potential agricultural applications, highlighting this approach's environmental and economic benefits. Therefore, drying industrial sludge emerges as a crucial initial step for the reuse and recovery of industrial waste, contributing to the sustainability and efficiency of industrial processes.

Developing sustainable technologies for treating and reusing industrial sludge has been the subject of intense research in recent years. In this work, two prototypes of industrial sludge drying equipment were developed using solar energy as an energy source. The first has already been tested, and the second is under construction. This innovative approach seeks not only to reduce operating costs but also to minimize the environmental impact associated with the treatment of industrial waste. Studies such as Santos et al. (2023) have explored this emerging technology, highlighting the effectiveness of solar energy in drying industrial sludge and its potential benefits in terms of sustainability. By harnessing the abundant solar energy available, these new prototypes present a promising alternative for drying industrial sludge, paving the way for more efficient and environmentally conscious management of industrial waste.

The first prototype, shown in Figure 8, was a hybrid active indirect solar cabin dryer. The proposed dryer had a drying tray with an area of 0.108 m^2 (0.24 m × 0.45 m). The drying capacity was estimated at approximately 2 kg of wet sludge per batch. The airflow was forced convection by a fan at the inlet. Developing drying kinetics with solar energy on a laboratory scale allows a new prototype to be designed on an industrial scale.

Figure 8 - Photo of the active indirect solar dryer: (A1, A2, A3, A4, and A5) PT-100 temperature sensors, (B1 and B2) thermo-hygrometer, (C) pyranometer, (D) anemometer, and (E) photovoltaic panel.



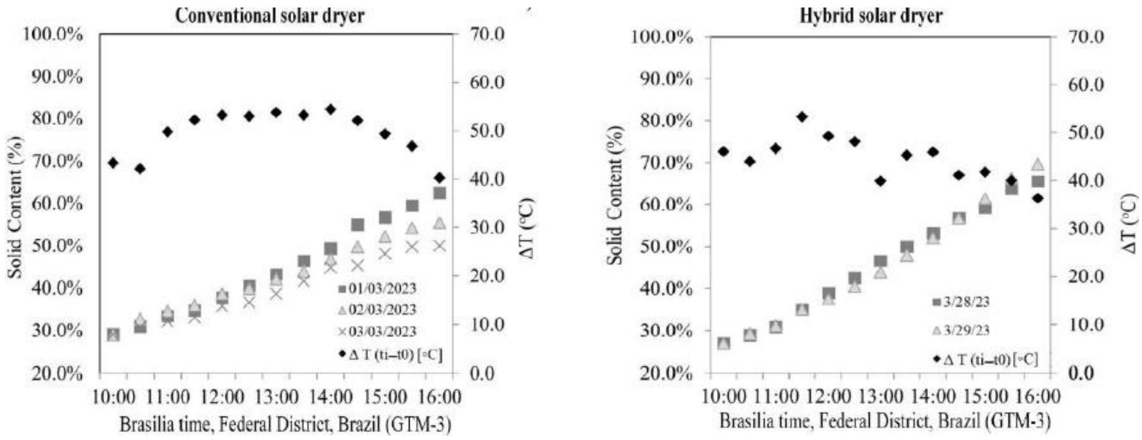
Source: Gonçalves *et al.* (2023).

The partial incidence of solar radiation passes through the glass cover and reaches the matte black-painted absorber plate. Hot airflow removes moisture from the product through a rectangular section (chimney). The product was inserted into and removed from the drying chamber through the door at the back of the equipment. The experiments were carried out over four days in November 2023. Four tests were carried out to assess the influence of weather conditions on the fluid-dynamic behavior of the heated air. During the experiments, solar radiation, ambient temperature and relative humidity, outlet velocity, and inlet and outlet temperatures were recorded using the sensors as shown in Figure 8.

Drying tests were carried out on primary sludge from a pulp industry WWTP in northeastern Brazil, from 10 a.m. to 4 p.m. Brasília time, Distrito Federal, Brazil (GTM-3). The reduction in moisture in the samples was monitored by weighing them at regular intervals of 30 min. The sludge was loaded into four trays with a capacity of 0.5 kg each and placed in the drying pile inside the equipment's chimney, totaling a load of 2 kg of sludge for 6 hours of drying. The equipment construction cost was approximately USD 502.00, and it was designed and built in approximately four months. The moisture content was measured when the waste in the solar dryer reached hygroscopic equilibrium. Curves representing the relation between drying time and moisture content were derived based on the moisture content at the end and during each drying time interval.

During the tests, the temperature and relative humidity of the air at the inlet and outlet of the dryer were evaluated (using two thermo-hygrometers), the air speed at the inlet of the dryer (using an anemometer), and the solar radiation (using a pyranometer) were measured, comparing the drying mode in conventional mode (solar radiation only) and hybrid mode (adding heated air through a heat blower). Drying curves were determined for each solar drying test, as shown in Figure 9.

Figure 9 - Drying curves observed for the test of the Solar Dryer Prototype 1.



Source: Gonçalves *et al.* (2023).

The drying curve shown in Figure 8 indicates greater attenuation in the first few hours of the test, resulting in greater surface water removal from the waste. The results of the drying test carried out from March 1 to 3, 2023, with the conventional solar dryer started with 29% initial solid mass, and at the end of the drying tests, a solid mass content of 62.5% was reached. On March 28 and 29, 2023, tests were carried out with the hybrid solar dryer, starting with a solids mass of 27%, and at the end of the tests, an average of 69.6% solids mass was obtained.

After analyzing the results obtained in the preliminary tests of the initial prototype, work began on the design and construction of a new model to achieve better results in the efficiency of industrial sludge drying. The first modification to the initial version concerns the preheating of the air with the addition of air heated by a heat blower. In the second prototype, a solar vacuum heating system, commonly used to heat water for bathing, will be used, which will allow the air heated by solar radiation to be stored. This approach aligns with research by Santos et al. (2021), who highlight the effectiveness of solar vacuum heaters in reducing energy consumption and increasing the efficiency of industrial drying processes.

In addition, the use of solar energy will be integrated into all phases of the process, for thermal and electrical purposes through photovoltaic panels promoting forced convection through a mini-fan. All the sensors will be powered by the electricity grid originating from the photovoltaic panels of the Solar Plant at the Florestal Campus of the Federal University of Viçosa, where the second prototype will be installed (Figure 10).

Figure 10 - Photovoltaic Energy Laboratory located at the Federal University of Viçosa - Florestal Campus.

Source: Authors.

Finally, the sludge will be directly exposed to the sun, which will also help to increase efficiency in the drying process. This approach is in line with recent studies, as highlighted by Santos et al. (2023), which highlight the benefits of direct exposure to the sun in the industrial waste drying process, resulting in a reduction in drying time and an increase in the system's energy efficiency.

This second prototype is a mixed solar dryer that uses solar energy directly and indirectly to dry industrial sludge. It was built using two technologies: a greenhouse dryer used for drying rice (Chan et al., 2015) and a mixed dryer used for drying tomatoes (Nayanita et al., 2022).

The proposed system has a vacuum tube heater coupled to an adequately insulated water recirculation boiler, which is responsible for preheating the air at the entrance to the oven, transforming it into a mixed drying system, and all the sensors installed to measure essential parameters. This drying system can be scaled up for industrial application, favoring the use of sludge and other industrial waste to contribute to the reuse of wet waste in general and thereby help industries reduce environmental impacts.

To build the prototype, the following activities were carried out:

- Literature review;
- Pricing research and costing of the project.
- Adaptations to the models found in the literature that favor the development of technology in order to include the use of direct and indirect solar energy.

The construction of the prototype is based on two fundamental studies. Chan et al. (2015) developed a solar dryer with an integrated collector drying chamber, as shown in Figure 12, consisting of a transparent polycarbonate structure, a solar plate, and a fan to promote airflow inside the chamber. In addition, the prototype incorporates a greenhouse-type dryer equipped with a vacuum solar heater, consisting of tubes connected to a boiler for water recirculation, as shown in Figure 11, thus configuring itself as a mixed dryer (Nayanita et al., 2022).

Considering these elements, the dryer uses direct and indirect solar energy:

- By directly absorbing the energy through the black plate on the roof of the greenhouse cabin.
- And indirectly through the vacuum solar heater, which is a tube heater (one tube inside the other fixed by fusion), where the water that passes through the tube receives solar radiation, heats up to around 100º C, passes through the boiler and exchanges heat by conduction and convection with the air located in a copper coil inside the boiler. This preheated air enters the drying chamber and dries the sludge.

The prototype's dimensions are 0.7 m wide by 1.2 m deep. The equipment has a rectangular geometric structure with an inclination of 30°. It has an exhaust fan at the outlet, capable of extracting the ambient air that passes through the boiler and the samples. The structure is made of glass on the top and two sides, while the front and back are made of a metal structure filled with glass wool or ceramic fiber and painted matte black to maximize the absorption of solar energy.

Unlike conventional solar heater models in which the water circulates, the water stands still in this prototype, circulating only inside the boiler. Inside the boiler, there is a layer of cold water that, as radiation becomes available, will heat up, reducing the amount of cold water and increasing the amount of hot water until the boiler is completely filled with hot water. The air enters from the right side of the unit through the 8 copper tubes and it is drawn in by the exhaust fan, circulating inside the unit and exiting through a 60 mm conical tube and an accordion exhaust hose that can withstand high temperatures.

The prototype was built in two parts. The first part involved inserting the tubes into the boiler (Figure 11). The second part involved constructing the greenhouse based on the studies by Chan et al. (2015), illustrated in Figure 12.

Figure 11 - Modified boiler with insertion of copper tubes for Prototype 2 of the solar dryer.

Source: Authors.

Figure 12 - Main components of the greenhouse solar dryer.

Source: Chan et al. (2015)

Adopting solar sludge dryers in Brazil and worldwide would bring numerous benefits. To begin with, it could substantially reduce the environmental impact of waste disposal by minimizing the volume of sludge generated and increasing the content of solid materials through moisture reduction. This, in turn, would reduce dependence on conventional landfill methods, contributing to a more sustainable waste management approach. In addition, solar drying presents a cost-effective and energy-efficient alternative to traditional drying methods. As solar energy is readily available in Brazil and many other regions, harnessing this renewable resource for drying processes can significantly save energy costs and operating expenses.

It is worth noting that during the project's development, the doctoral students write technical articles for the final thesis. The writing is usually the result of discussions with various collaborators, many of them from other research institutions and universities in Brazil or abroad, such as UFVJM, UNIFEI, and LUT.

6. General Engineering Competences Matrix: Integrating PjBL into Pilot Plant Projects

According to the National Curriculum Guidelines (DCN) for Undergraduate Engineering Courses, the profile of the graduate of the undergraduate engineering course is expected to include the following characteristics (DCN, 2019):

- Holistic and humanistic vision;
- Technical degree/training;
- Incorporation of digital technologies;
- Interdisciplinarity and multidisciplinary approach;
- Engineering problem-solving;
- Ability for evaluation.

Table 1 shows the skills and knowledge developed by the students in each project based on the challenges faced, with segmentation following the DCN.

Table 1 - Skills developed in the projects.

Skill	Experience 1	Experience 2
Holistic and humanistic vision	During the causticizing stage, the pulp and paper industry deals with various parameters that impact the quality of the white liquor. Since carrying out tests on an industrial scale is unfeasible, either for financial or safety reasons, developing a pilot plant makes it possible to study this stage without the aforementioned disadvantages. Furthermore, developing such a project in a university environment fosters multidisciplinarity and engages and motivates students to develop technical skills through active methodologies. One of the crucial points is the proactivity that has made it possible to develop, in other words, the interdependence of the student, which enables greater efficiency in the development of tasks.	This initiative provides a valuable hands-on learning environment for students, allowing them to apply theories learned in the classroom to real-life situations. In addition, a university pilot plant offers the opportunity to research and develop innovative technologies, contributing to scientific and technological advances. From a humanistic perspective, the pilot plant can serve as a space for interdisciplinary collaboration, bringing together students and researchers from different fields to address complex challenges in an integrated way. This holistic approach not only promotes academic excellence but also fosters values such as environmental responsibility, sustainability, and social awareness, preparing students not only for their careers but also to be engaged and conscientious citizens.
Technical degree/training	The development of the pilot plant for the causticizing stage of the Pulp and Paper Industry's Kraft Process enabled the application of technical knowledge developed in various curricular subjects such as heat transfer, fluid mechanics, technical drawing, and process design. The students could associate theory with practice, identifying the equipment and devices in the plant. This ability enabled them to build up a technical view of the process, helping to improve the processes in the laboratory. In addition, the students discussed issues related to the control and instrumentation of the pilot plant so that in future stages, the process can be automated and operated remotely, for example.	The construction of a pilot plant for industrial sludge drying equipment involves the application of various concepts and disciplines mainly related to the Chemical Engineering course. One of the fundamental aspects is the selection of suitable materials to withstand the operating conditions and the chemicals in the sludge. In this sense, knowledge of corrosion and materials is essential to ensure the durability and safety of the plant. In addition, thermodynamics is crucial for the efficient design of the drying system, considering the heat and mass transfer processes involved. Chemical kinetics also plays an important role in optimizing drying times and equipment efficiency. Process control aspects, such as the design of automation and instrumentation systems, are essential to ensure the stable and efficient operation of the pilot plant. Finally, environmental issues, such as effluent treatment and atmospheric emissions, are also important considerations, requiring knowledge of environmental engineering, as well as skills related to modeling and simulating drying processes.
Incorporation of digital technologies	During the development of the PFD, flowchart, and 3D visualization of the Pilot Plant, the students used AutoCAD software for virtual design. In addition, MS Excel was used to solve partial differential equations using the Orthogonal Placement numerical method. Not least for data acquisition during the tests, electronic devices were used to collect data in real-time.	Computational modeling and simulation play a crucial role in the design phase, allowing professionals to predict the behavior of the equipment and optimize its performance before physical construction. Simulation tools such as Computational Fluid Dynamics (CFD) are used to analyze the flow of air and heat inside the dryer, helping to optimize design and energy efficiency. Implementing sensors and devices is also key, as it provides real-time data on temperature, humidity, and other critical process variables. This data can be analyzed, allowing continuous plant performance optimization and early detection of potential problems. In addition to using software that enables mass and energy balancing, such as Aspen Plus. And GABI software, which enables Life Cycle Analysis (LCA) to help make decisions regarding critical points in atmospheric emissions.
Interdisciplinarity and multidisciplinary approach	During the project's development, the students were responsible for defining the plant's operating parameters. To do this, they used knowledge from various fields, such as electrical engineering to install the heating system; heat transfer to understand how the proposed heating system works; fluid transfer to size valves and pipes in order to guarantee the least possible fouling; corrosion engineering, given the high alkalinity of the solutions used, in order to guarantee safety during the operation of the process; process safety, given the use of temperatures of around 100°C and reactions in a basic environment; ergonomics, given that the project aims to ensure quality in the health of the pilot plant operator; economic evaluation of the project, to ensure efficient management of the financial resources used in the project; project management, given that this is a long-term project with a high turnover of participating groups.	Building a pilot plant for industrial sludge drying equipment requires an interdisciplinary and multidisciplinary approach that integrates knowledge from various areas of engineering and applied sciences. Chemical engineering plays a central role in understanding drying processes, selecting materials, and designing control systems. On the other hand, mechanical engineering is fundamental to the design and construction of equipment, such as the dryers themselves, guaranteeing functionality and durability. Electrical and electronic engineering contributes to integrating automation and control systems, while materials engineering is essential in selecting resistant and efficient materials. In addition, environmental engineering plays a critical role in considering the environmental impacts of the process, as well as the proper management of waste and emissions. In addition to engineering disciplines, areas such as computer science and information technology are crucial to implementing digital control and monitoring systems.

Engineering problem-solving	The project's main engineering challenge was to develop a pilot plant layout that considered safety and good operating conditions. In this respect, the students were responsible for drawing up a layout (2D and 3D) considering fluid and heat transfer relations, as well as the chemical kinetics involved in the causticizing stage. Experimental tests were carried out to validate the proposed equipment, which ensured mathematical modeling of the heating and pumping systems. At the same time, the selection of corrosion-resistant materials and a temperature of 100°C were evaluated since these parameters are important in terms of the useful life of the pilot plant and the safety of the process. Not least, the students also installed a control panel in the pilot plant layout to automate the pilot plant using devices that measure parameters such as temperature, flow, and level in real-time for future remote operation of the pilot plant.	This activity involves solving a series of complex engineering challenges. One of the main challenges is the design of the dryer itself, taking into account factors such as the type of sludge to be processed, the operating conditions required for effective drying, and the system's energy efficiency. This requires the application of thermodynamic principles, heat, and mass transfer, and knowledge of chemical kinetics to ensure adequate drying times and final product quality. In addition, selecting corrosion- and wear-resistant materials is crucial for the durability and useful life of the equipment. The integration of control and automation systems also presents challenges, requiring the implementation of sophisticated algorithms to ensure the stable and efficient operation of the dryer. Waste and emissions management is another critical issue that requires innovative and sustainable solutions involving effluent treatment and pollution control technologies. Solving these engineering problems in the pilot plant construction requires a careful approach based on data and experimental tests and close collaboration between various engineering disciplines.
Ability for evaluation	"Developing the pilot plant allowed us to apply the knowledge we had acquired during the course differently to what we had experienced during our degree. From the project, it was possible to see the interdisciplinarity between the curricular subjects and the importance of learning acquired beyond the classroom." (L.L.C.C.) As reported by the student, the project to develop the pilot causticizing plant allowed those involved to use the technical skills developed during their degree to prepare an engineering project. In addition, the students were challenged to develop the project by reusing unused equipment from the laboratory. They were responsible for validating the use of such equipment against the operating capacity designed for the pilot plant. Finally, given that the project involves different stages, the students listed suggestions for future work, such as implementing and testing the control panel; developing the filtration system; building the other causticizers; carrying out pumping tests with the three causticizers.	Building a pilot plant offers students valuable opportunities to apply and hone their evaluation and problem-solving skills. During the planning and construction process, students are challenged to analyze and evaluate various technical and operational aspects, such as the choice of materials, equipment sizing, control and automation requirements, and environmental considerations. They must carefully consider the limitations of the project, such as costs, available space, and safety constraints. In addition, students are encouraged to carry out experimental tests and simulations to validate the equipment's performance and identify possible improvements. This is an important project for developing students' critical and analytical mindset. By facing real challenges and making informed decisions throughout the construction process, students are preparing to face the challenges of the professional world with confidence and competence.

Source: Authors.

The advisors Cardoso and Oliveira report that the use of prototype equipment and pilot plants tends to increase student participation and motivate them during the project. In addition, the students demonstrated better teamwork skills and increased collaborative interaction, and there was a rapprochement between academia and the pulp production sector.

7. Conclusion

Historically, engineering courses have been based on traditional teaching tools, which no longer meet the needs of the professional training required by today's market. In this sense, applying active learning methodologies, in which students actively participate in the learning process, is fundamental to guaranteeing the quality of higher education. Therefore, implementing project-based methodologies is an important ally of academia in students' technical and professional training, as it provides collaborative environments that enable real problems to be solved.

Within this context, project-based learning, in which interdisciplinarity and teamwork are applied, has been used at the Federal University of Minas Gerais with undergraduate and postgraduate students in the field of Engineering. In an integration between academia and industry, two challenges in the cellulose pulp manufacturing process were considered: the difficulty of controlling causticizing efficiency and the high generation of sludge in the effluent treatment plant with high moisture content.

In order to propose solutions to the first bottleneck, a group of Chemical Engineering students was responsible for starting to implement a pilot plant in the Operations and Processes Laboratory at the Federal University of Minas Gerais. Initially, the activities involved understanding the Kraft process and the challenges to be faced, reviewing the literature on the subject, and building the process flowchart and plant layout using AutoCAD. Adaptations were then made to the equipment available in the laboratory, such as installing electrical systems. During this phase, the focus was on the heating and pumping systems, and the tank's operating curves were obtained in relation to temperature and the volume of water fed. The work will continue in the following academic semesters to finalize the pilot plant's implementation, which includes installing a control and automation panel.

Regarding sludge production, doctoral students have developed two prototypes of industrial sludge drying equipment that use solar energy. The first was an active indirect booth dryer. The instantaneous thermal efficiency of the dryer varied between 8.4% and 28.2%, and the highest percentage of solids obtained was 69.6%, starting with a mass of 27%. Based on the analysis of these results, a second prototype is being built to optimize the efficiency of the equipment and the sludge drying process. It will be a mixed solar dryer that uses direct and indirect solar energy for drying. In this case, a vacuum solar heating system will preheat the air, and the sludge will be directly exposed to the sun. As a novelty compared to conventional models, the water used circulates only inside the boiler.

In both activities, the students involved could apply the technical knowledge developed in the various curricular subjects to real problems in the pulp and paper industry in an interdisciplinary way. By actively participating in the development of the projects, they identified that they had developed the skills and competencies described in the National Curriculum Guidelines for Engineering courses, such as a holistic and humanistic vision, the ability to incorporate digital technologies; interdisciplinarity and a multidisciplinary approach, solving engineering problems and the ability to evaluate. This evidence, therefore, confirms that the development of prototypes and pilot plants for teaching engineering provides training for professionals prepared to meet current market demands.

To continue studies in this direction, the group suggests completing the laboratory's pilot plant with the other stages of the Kraft pulp and paper process, as well as proposing improvements to the dryers to increase the efficiency of the equipment.

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