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STAINLESS STEEL AUTOCLAVE SANDING DEVICE: A CASE STUDY ON A MECHANICAL ENGINEERING PROJECT-BASED LEARNING COURSE

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Abstract. *This paper describes the approach and the resulting solution developed under the scope of a project-based learning course within the Federal University of Santa Catarina's Mechanical Engineering bachelor. This approach aims to develop and exercise the students' abilities in project design and enhance their view and understanding of the market expectations, and from real industries' demands. In this context, a group of undergraduates, under the supervision of an advisor professor, was responsible for the proposition of new solutions for a machining device capable of sanding surfaces inside cavities. The current machining process reported by autoclave manufacturers is an expensive, long and insalubrious process as autoclaves present a squared-section long duct, considerably narrow for manual labor. Furthermore, the material, stainless steel ASTM 316-Ti, presents challenges to the machining process due to its austenitic nature, impacting the thermal conductivity in a high heat generation process. In addition, the presence of titanium enables the formation of Ti-CN (titanium carbo-nitride) groups, which are abrasive and harder to machine. In terms of methodology, given the project challenge, the development started by determining the user's and the project requirements, the state-of-the-art of the presented machining configuration, patents and standards research, and similar products review, activities which comprise the planning, informational and conceptual development phases, respectively. After deciding the initial layout, the group was divided into project areas: structure, displacement, tool-to-piece contact, and machining, in order to perform the so-called preliminary and detailed phases of development. As result, aside some industries' interest in the resulting solution, from the learning perspective, the course presented a fertile and engaging environment for the application of technical knowledge acquired during the graduation course, such as project management, project methodology, solid mechanics, vibration, machining and machine elements.*

Keywords: *project based learning, product development process, machining, sanding device*

1. INTRODUCTION

The so-called "Integrated Project" is a project-based learning course within the Federal University of Santa Catarina's Mechanical Engineering Bachelor's. The enrolled students are divided into groups, each supervised by a professor, and the objective is to apply the technical knowledge acquired during the undergraduate studies onto real Mechanical Engineering demands. The present case-study regards the work of eight undergraduate students enrolled in the referred course, for which the challenge was to create a new sanding device capable of machining stainless steel surfaces inside autoclaves, in order to reduce the insalubrious manual labor of this activity. The actual machining process reported by a local autoclave manufacturer is non-ergonomic for the operators, as the autoclave chamber is a squared-section long duct, considerably narrow for manual machining operation.

The autoclave cavity results from two U-shaped profiles, entirely made of stainless steel ASTM 316 Ti which are welded upon each other. The squared cross-section may vary from 440 mm to 660 mm and has rounded corners. Its length also vary from about 750 mm to more than 2000 mm. The autoclave is formed by other parts as well, but the scope of this work is restricted to the cavity. The time required to machine a single autoclave corresponds to 41% of its total production time, taking, on average, 22 hours to sand it and additional 5 hours to polish it. The chamber is placed on a support with external arcs to rotate it and place horizontally the internal surface, as shown in Fig. 1. The operators machine the internal surface with angle grinders with flap discs. They work for several hours leaning towards the surface and are exposed to high levels of noise and a dusty atmosphere. In addition, the process consumes several angle grinders and flap discs per year and face mask filters, since the process generates a lot of heat and dust. The filters given to the workers (masks) and those used in the exhaust system correspond to more than 1/3 of the costs with consumables. Therefore, alongside the main goal of reducing the manual labor, a sanding device is expected to reduce secondary costs, i.e. individual protective equipment and exhaust filters, and possibly reduce the duration of the process.

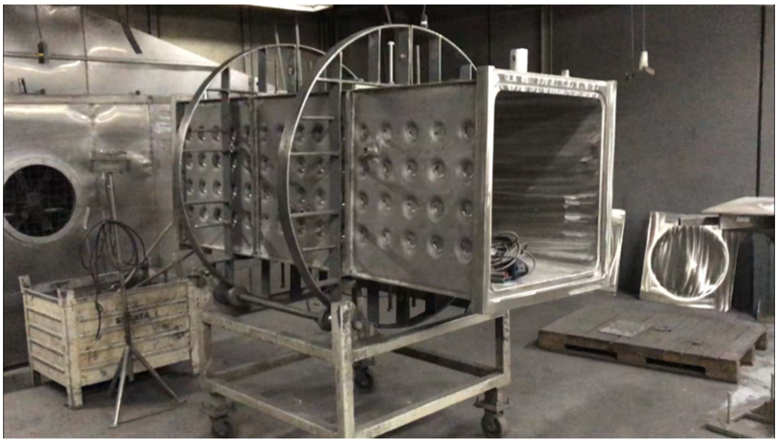

Figure 1. Autoclave placed on the support. Source: Authors (2021).

2. LEARNING MODELS IN ENGINEERING

It is widely recognized by the scientific community that classical engineering teaching - famously termed as "sage on the stage" - corresponds to the figure of the professor and is theory-centered, leaving the students to play a passive role (Boehs *et al.* (2015); Shekar (2014); King (1993); Dinis-Carvalho and Lima (2006)). Such approach is counter productive to the goal of training new engineers, which not only need learn meaningful technical knowledge of the field, but also need to be capable of applying them proficiently in solving novel, complex and real problems. In order to fix such inconsistency, various models have been proposed to improve students' engagement in learning, as well as to help them develop the soft skills and mental conditioning that compose the skill-set of highly successful engineers, as pointed out by Litzinger *et al.* (2011).

This subject is rich and has been studied for decades, with several learning methodologies, forms of applications, ideas and principles being proposed and discussed. A thorough review and evaluation of the methodologies, their characteristics and forms of applications will not be presented in this section, and not comprise the scope of the present research. This section will shortly describe four relevant and up to date methods: Flipped Classroom, Problem-based learning, Project-based learning and Problem- and Project-based learning.

2.1 Flipped classroom

Flipped Classroom is a teaching model which consists in having the students to study course resources (e.g. online videos, assignments, literature, text-books) beforehand in preparation for each class, so that such encounters may serve as an opportunity to engage all students in interactive, collaborative and hands-on activities, such as problem-solving, brainstorming, discussions on particularly difficult topics, among many others. The difference of traditional learning to Flipped Classroom Model is presented in Fig. 2. The purpose of this model is to encourage the students to play an active role in class and help them learn many skills which are important for a professional aside from the technical aspect.

Many studies were conducted to determine not only this model's efficacy in providing a more robust learning experience to the students, but also to identify the students' perception of the model. Most of them conclude that the flipped classroom model is more effective than traditional learning and, although some students are resistant to the model, most of the papers reported that students tend to enjoy the model after going through an adaptive period, as discussed by Kerr (2015); Karabulut-Ilgu *et al.* (2018); Bhat *et al.* (2020).

Even though scientific evidence points to the efficacy of the model for student learning, the flipped-classroom has been found hard to apply due to the difficulty in engaging all students in meaningful activities, specially when dealing with large groups, as the instructor's workload increases - since he needs to prepare and integrate both out-of-class and in-class activities (Kerr (2015); Bhat *et al.* (2020)).

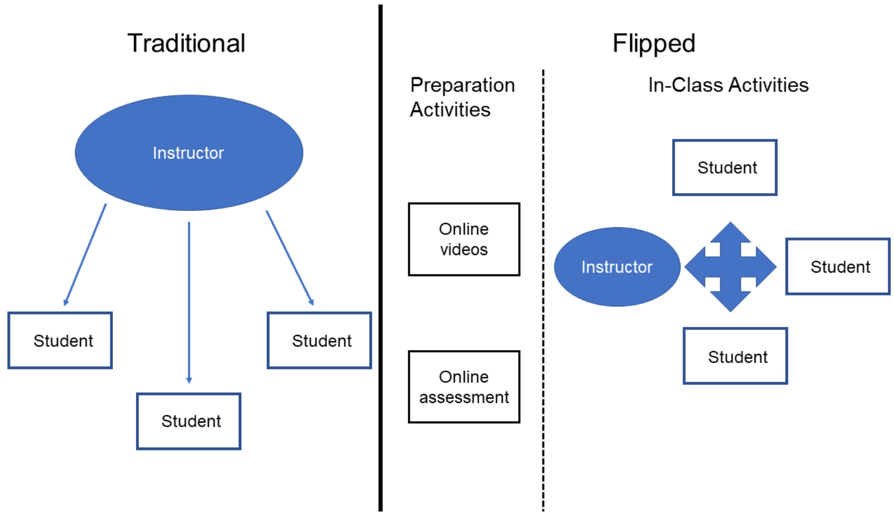

Figure 2. Difference of traditional learning to the Flipped Classroom Model. Source: adapted from Bhat *et al.* (2020).

2.2 Problem-based learning

Problem-based learning consists in a student-centered approach to constructing knowledge. While the classic "sage on the stage" establishes an instructor who shares knowledge with the learners, one of the principles of the problem-based approach is that "knowledge is individually constructed and socially co-constructed from interactions with the environment; knowledge cannot be transmitted", as stated by Woei Hung (2007).

The general characteristics of Problem-based learning, according to Woei Hung (2007); Savery (2006), are listed below:

- Students are divided in small teams and a tutor is assigned to supervise and facilitate the processes;
- Students must have the responsibility for their own learning. It is student-centered, self-directed, self-reflective, and leans on self-assessment and peer assessment. Assignments are rare;
- Tutors are facilitators instead of instructors. They support and model reasoning processes, facilitate group processes and interpersonal dynamics and probe students' knowledge deeply. They do not express their opinion on the project course nor provide direct answers to questions;
- The problem simulations used in problem-based learning must be ill-structured and allow for free inquiry;
- Learning should be integrated from a wide range of disciplines or subjects. The content and skills to be learned are organized around problems so a reciprocal relationship exists between knowledge and the problem;
- Collaboration is essential;
- What students learn during their self-directed learning must be applied back to the problem with reanalysis and resolution;
- A closing analysis of what has been learned from work with the problem and a discussion of what concepts and principles have been learned is essential;
- The activities carried out in problem-based learning must be those valued in the real world;
- Student examinations must measure student progress toward the goals of problem-based learning.

Summarizing, this method relies heavily on student self orientation to solve a ill-defined problem. In other words, it is up to the students to determine their goal setting, strategy, problem solving, tasks execution, learning materials, and so on. The tutor or academy defines no expected outcome so that the whole process and method of resolution come from the learners themselves. It has been reported that learners who undergo through such process tend to be above-average in life-long learning aspects.

2.3 Project-based learning

Project-based learning is quite similar to Problem-based learning in being a student-centered and seeking to encourage self-learning, self-managing, and collaborative work in order to achieve a determined goal. The main differences, according to Savery (2006), consist in the fact that Project-based learning tends to favor "correct procedures" that can be applied in order to achieve a predetermined outcome. The list below points out the unique traits of Project-based learning approach in comparison to the Problem-based approach according to Savery (2006); Brundiers and Wiek (2013); Wiek *et al.* (2014).

- Specific understanding is sought and applied to obtain practical products;
- Focus on producing applicable results based on evidence;
- While still being student-centered, the Project-based learning organizes students according to a determined project management structure;
- Tutors act as instructors, coaches and consultants, being able to provide expert input in the project, and provide specific answers to problems when available;
- Predetermined desired outcomes are set and expected to be aimed at by the students.

The differences displayed provide evidence of the uniqueness of the Project-based approach. And while not as focused on student self-management and orientation as the Problem-based approach, it still provides an environment where the students can develop their soft skills, collaborate and direct their learning in multidisciplinary subjects in order to achieve a goal. Or, in this specific case, to develop a product which solves a specific problem (Fernandez-Samaca and Ramirez (2010); Dinis-Carvalho and Lima (2006); Brundiers and Wiek (2013)).

2.4 PPBL - Problem- and Project-based learning

The Problem- and Project-based learning approach (PPBL) aims to intersect between the Problem-based and Project-based approaches. Brundiers and Wiek (2013); Boehs *et al.* (2015) explain that the idea is to build on common ground, like promoting the students' self-orientation and assessment and collaborative work, but also capitalize on each method's advantages. For example, this method follows a problem-based approach in understanding and addressing the initial problem, and then making use of the project-based learning principles to develop effective solutions.

The main focus of this method is to provide students with real world problems in which they can apply the principles of problem and project based learning in order to generate knowledge in the form of novel solution options, as explained by Brundiers and Wiek (2013). Wiek *et al.* (2014) states that such goal is achieved by and iterative process where the student performs peer- and self-evaluations to improve the quality of the team's and the self's activities, critical thinking abilities and the quality of outputs, and in turn he will be more prepared to engage in multidisciplinary, collaborative and innovative work to solve real world problems in the future.

3. METHODOLOGY

The learning approach applied in the "Integrated Project" course was Project-based, which means it was student-centered and focused on applicable results and product development. The students were separated in groups assigned to different instructors - each with a determined field of expertise - which acted as guides and consultants to facilitate the design process and teach relevant principles. The group analyzed in this case-study was composed of eight people, plus the instructor. The product development process to be applied during the course by all students was the PRODIP (Integrated Product Development Process) method (Back *et al.* (2008)), which list specific steps and activities of the designing process that should be satisfied while preserving the group's autonomy in decision-making. The PRODIP model is presented in Fig. 3.

In the case of this research, for the development of the sanding device the group focus was given entirely to the engineering design stage, once the planning stage was given as input (i.e. challenge) by the client itself, and the implementation stage is yet to be determined according to the resultant solution proposal. The approximate 112 days which encompass the Integrated Project course allowed the team to act over the informational, conceptual, and preliminary phases, being the work planned over 16 weekly sprints. The sprint, a tool borrowed from the agile frameworks, was the way of managing a project with such a complex scope for the available deadline the team thought to have the best fit.

As mentioned earlier, it is important to comment that the original eight-member group was divided also into four subgroups, each one responsible for one device subsystem, that had been listed in the product functional synthesis during the first days of work. The subgroups were: machining, movement, support, and pneumatics, each having a leader responsible for distributing tasks and tracking the progress.

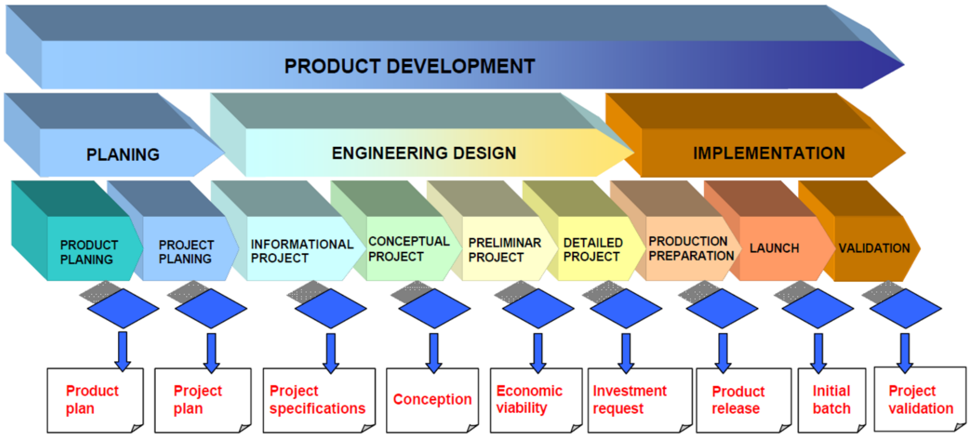

Figure 3. PRODIP model for the product development process. Source: adapted from Back *et al.* (2008).

During the sprints each subgroup worked in their own demands, and communicated with each other through the Microsoft Teams, the platform used for keeping the project files and to centralize the conversations (i.e. to guarantee the registration and information traceability). Once a week the group gathered, with the participation of the professor supervisor, to share what had been done, what were the difficulties, and which should be the next steps. This was the dynamic that marked the job as a kind of weekly sprint, in the sense of the agile development framework. Whenever a technical issue arised, it was largely discussed by the whole group, including the professor as adviser, in a second moment of the meetings, which was dedicated to problem-solving. In cases where some specific technical knowledge domains was required other professors where engaged as specialists consultants. The contact with the industry which presented the challenge during the development was encouraged whenever information, ideas and technical validations were necessary.

4. RESULTS

In this section the technical development of each subsystem that compose the device envisioned by the group to face the challenge proposed is presented. The aim of this section is to demonstrate the depth of the technical knowledge that the students had to deal with during the course in order to relate the information with the Project-based learning particularities presented previously.

4.1 Machining subsystem

The machining process was the source of most changes in the concept, being responsible to address the necessities of robustness, stability, movement, heat generation, productivity, assembly time. The first subject researched was the characteristics of the material to be machined - stainless steel ASTM 316-Ti - and its impact on the machining process. This steel possesses low thermal conductivity, austenitic structure, a titanium presence which may generate abrasive groups hazardous to the machining tool, high tenacity, and other characteristics which impose a challenge to machining, according to Machado *et al.* (2015).

The grinding wheel was elected for the first conception. The non-defined geometry processes for material removal on metals area is still in development in the literature, putting the group in a position where catalogs were the most helpful sources, and the knowledge of professors and industry experts was essential. This led to two main materials for the wheel grains, cubic boron nitride (cBN) and silicon carbide, as indicated by an specialist, in addition to the lubrification/refrigeration with compressed air (Nakayama *et al.* (1987)). Nonetheless, grinding wheels have two main problems for the present application: the wheel thickness, commercially limited to one inch (Krebs and Riedel GmbH. (2020), Norton Industrial (2014)), raised productivity reasons, while the need for a very robust structure to accommodate the natural wheel vibrations, risking shattering the wheel. When confronted with these challenges, and consulting professors, the team decided to switch the tool to the sanding belt.

The sanding belt overcomes these concerns. The new challenge, especially on how to accommodate the belt on the structure, can be overcome by proper engineering, which is exactly the goal of the course. The sanding belt grinding of metals is an area less explored in the literature, with only the recommended grain materials being explicitly stated (Finishing Technologies Inc. (2020)), and all the other parameters being limited to general instructions of how to define the optimum condition. The materials were selected by catalogs and a few other sources, being the silicon carbide and ceramic grains. Contrary to the wheel, the most important parameter for the proper machining and durability of the belt is not the cutting depth, but the applied pressure (Haas (2016)). Catalogs indicated only general instructions on how to define the best pressure, citing the symptoms of too big and too small pressure, but a few articles about sanding belt grinding on metals gave a pressure to begin with (around 400kPa) (Liu *et al.* (2011)).

4.2 Movement subsystem

The movement subsystem's main goal was to project the components needed to ensure that the machining solution would be able to work in all the coordinates and freedom degrees needed in the concept. The solutions were designed with this goal in mind and considering the following criteria: robustness, practicality and costs. For that, the movement was divided in four types: vertical, cross, longitudinal and support.

As an overview of the solutions it will be described the basic components of each movement's system. The vertical movement is performed by a stepper motor, which is translated by a trapezoidal thread spindle with ball guide and bearings. The spindle was chosen to be self-locking. The cross movement has the same components, distinguished only by the designed capacity. However the longitudinal movement required a distinguished type of guide with a built-in structural element, named v-slot linear rails. The spindle design was done following the catalog from HIWIN Global (2018) and THK Co (2021). Furthermore, the linear guide was designed following HIWIN Global (2020) catalog.

Last, the support movement was designed as a solution for the problem of stretching the belt accordingly to the longitudinal movement. This problem is illustrated in Fig. 4.

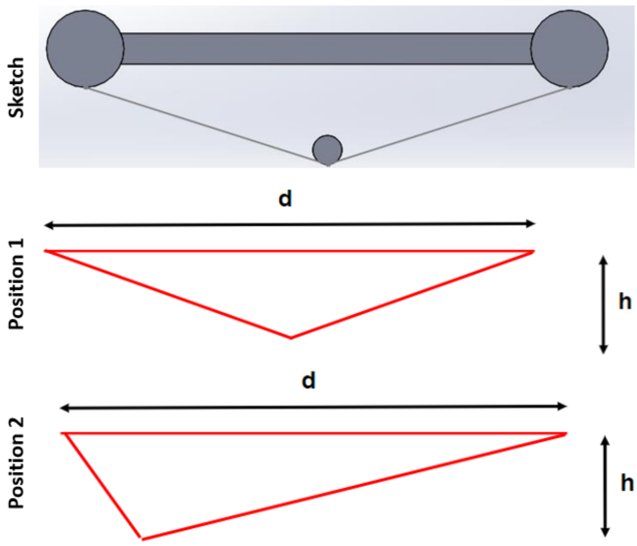

Figure 4. Height variation problem due to contact roller movement Source: Authors (2021).

The top of Fig. 4 shows a basic sketch of the machining solution. By this concept, it is possible to identify a problem of different required belt length depending on the tool's position. Considering the deployed situation, in which the distance "d" is equal to 1250 mm and height "h" is 200 mm hence constants, an extra length of 30 mm is required in the Position 2.To fulfill this requirement a belt tensioner was sketched using the GeoGebra software, giving the output of a minimum 80 mm required compression of the spring, as shown in Fig. 5

4.3 Support subsystem

The support area had the premise of ensuring the positioning and structural integrity of the machining and movement subsystems. In this sense, it was also up to the group to propose a layout that would satisfactorily accommodate all device components. The base structure that supports the beam and all other equipment is a tubular truss made of carbon steel in a format such that traction and compression requirements are printed on the tubes, avoiding moments in the knots.

The most challenging point of the support subsystem design is to find the best configuration to support the beam. The first concept adopted was a cantilever beam, as it would provide less setup time and fewer components in comparison to a clamped-clamped configuration. In this conception, the machining subsystem moves along the entire length of the beam during operation.

After the first evaluations of the concept through analytical formulations of beam theory, it was noted that its stiffness was insufficient to guarantee the necessary robustness. Furthermore, the movement of the machining subsystem along the length of the beam implied that the natural frequency of vibration changed during operation. When the engine was close to the clamped end of the beam, the natural frequency was slightly higher than the engine rotation, and when it was close to the free end, lower. Therefore, the natural frequency would coincide with the engine rotation at some point during the operation and high levels of vibration were expected.

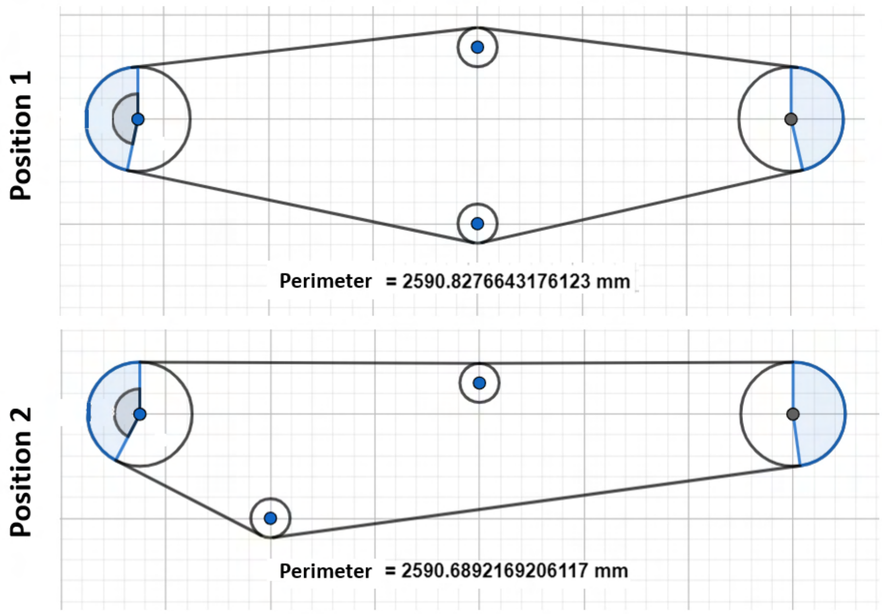

Figure 5. Belt tensioner sketched using GeoGebra. Source: Authors (2021).

Thus, the team decided to clamp the beam free-end using a mechanical jack like system that rests inside the autoclave to increase the assembly stiffness. In addition, a truss beam was designed, which provides greater rigidity with less mass compared to commercial profiles. This new setup and the adoption of the sanding belt allowed the team to place the engine at the clamped end of the beam. This new concept was re-evaluated through the Finite Element Analysis, and the stiffness and vibration parameters reached satisfactory values. The natural frequency has become at least five times greater than the engine rotation, which is placed in a position that does not dynamically excite the structure, and the moving parts are now lighter.

4.4 General considerations

The finished product consists of a semi-automatized sanding machine capable of providing internal surface finishing to prismatic tubes of significant size, shown in Fig. 6.

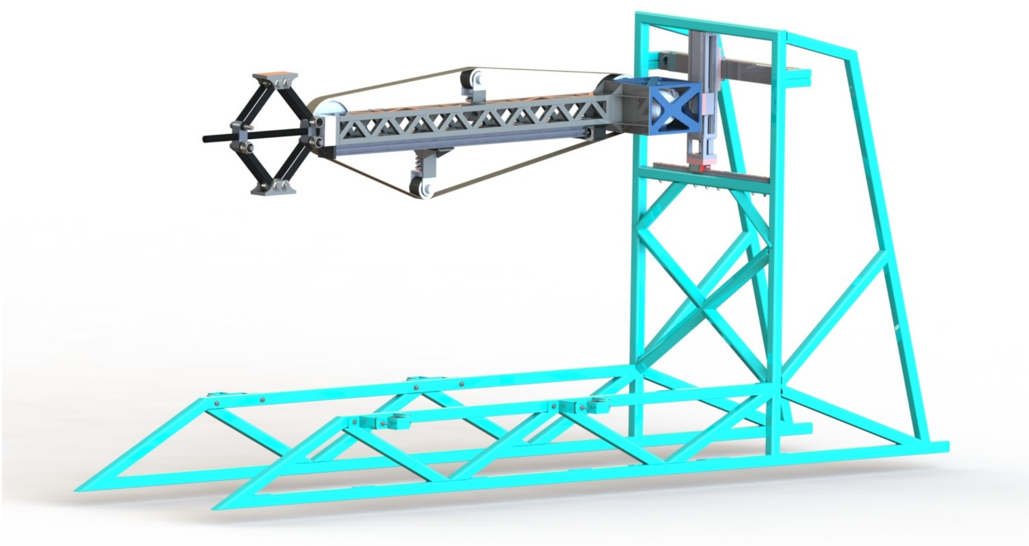

Figure 6. Final concept defined during the designing process. Source: Authors (2021).

The work conducted by the group, presented in the previous sections, highlighted that the development of a solution for a sanding device comprised an interdisciplinary effort, as well as soft skills, team work and organization to accomplish the challenge. All these characteristics could only be expressed and further developed through a non-traditional learning model such as the project-based learning. This approach adopted in the Integrated Project course presented a fertile and engaging environment for the application of several technical knowledge principles acquired during the Mechanical Engineering Bachelor's, such as project management, project methodology, solid mechanics, vibration, machining and machine elements. Moreover, the experience proved beneficial to the development of soft skills in the students. The development of a self-teaching attitude and problem-solving mindset is essential in a successful engineer, and such qualities became more apparent in the students by the conclusion of the project.

Along the course period, as the group evolved in organization and development of the project, a maturity growth was perceived by the students themselves and also by the challenging industry, to a point where the industry became interested in allocating resources to prototype the proposed device (solution). This outcome demonstrated the potential of the adoption of new learning models, and the strategic application of real industries' demand into graduation courses, as a powerful motivator. In addition, the device is currently under a patenting process.

This composition contributed primarily to the formation of better professionals and development of the sense of entrepreneurship within undergraduate students, and secondarily, indirectly, to the approximation of the university to the private sector. Such outcomes conform to the very goals of Project-based learning, which aims to better prepare students to work and deal with real world problems instead of simply transmitting theoretic knowledge.

5. CONCLUSION

The case-study presented the application of project-based learning model to an engineering course. Through the literature review, it was identified that the new learning models present the potential to favor knowledge acquisition, the development of problem-solving and soft skills, and are capable of engaging students along the course.

Through the observation of the work developed by a group of mechanical engineering undergraduate students during an integrated project course it was identified that an industrial real technical demand, as a challenge to a technical solution development, presented itself engaging and defying for the students. They had to organized themselves to face the requirements demanded and surpass difficulties that they would encounter in a professional environment.

Throughout the project the talks with external specialists proved to be an important asset for the achievement of outcomes, demonstrating how essential it is to study a project from multiple perspectives, as a multidisciplinary endeavor, to achieve critical analysis and effective solutions.

Regarding the project challenge, as difficulties arose from different technical areas, such as machining, vibration, solid mechanics, machine elements, and market analysis, the students could observe the inter and multidisciplinary characteristic of a real project endeavor. This facet favor the formation of professionals capable of having a holistic view, impacting directly their problem-solving ability and capabilities.

The course's outcomes, as highlighted in this paper, are aligned with the desired outcomes and goals of a Project-based learning approach. Some particularities of the project-based learning model, such as *Specific understanding is sought and applied to obtain practical products* and *Focus on producing applicable results based on evidence*, were the basis of the learning experience, leading directly to the achieved results. Therefore, it can be concluded that a successful implementation of this model indeed is capable of stimulating, engaging and contributing to students' formation, to a point were they, as professionals, and their work capabilities become capable of attracting industry interest and investment.

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7. RESPONSIBILITY NOTICE

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