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Analyzing Engineering Students' Creative Complex Problem-Solving and Higher Order Thinking Skills through Project-Based Learning

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Abstract— The study presented in this article provides evidence that project-based learning (PBL) is an effective pedagogical approach for enhancing student creative complex problem-solving (CCPS) skills. CCPS is a process that involves problem solving through creative thinking, analysis, and collaboration. PBL is an instructional approach that involves the development of student-directed projects to develop critical thinking, communication, collaboration, and problem-solving skills. The study was conducted in an engineering school in Canada, and its purpose was to examine the effects of PBL on engineering students' higher order thinking and CCPS skills. The results are encouraging, as they suggest that PBL can be a successful tool for fostering CCPS among students.

Index Terms—creative complex problem-solving, engineering education, problem-based learning, design skills.

I. INTRODUCTION

A growing number of undergraduate engineering programs in Canada have adopted an outcome-based approach, as noted by [1]. This shift has been prompted by national (CEAB) and international (ABET, Washington Accord, Bologna Process) policies that promote contextualized application of knowledge and active student engagement in teaching and learning methods. While retention and recall of knowledge are important cognitive skills to develop in a university setting, experts argue that the emphasis should now be on what individuals can do with their knowledge to solve complex problems in creative and innovative ways, especially in vocational training like engineering [2].

Complex problems require complex solutions that mobilize higher cognitive processes, including evaluation, analysis, interpretation, critical, logical, reflective, metacognitive, and creative thinking [3]. These cognitive processes are activated when learners face unfamiliar complex tasks involving high uncertainty, unanswerable questions, or multiple ways of implementation with various solutions.

Thus, creativity is a crucial skill for undergraduate engineering students. They must be able to think outside the box and generate novel ideas to solve complex problems and create innovations. Creativity entails identifying problems or opportunities, generating ideas, and finding solutions [4]. For engineers, engineering design focuses mostly on technological solutions.

Therefore, it is important for engineering students to identify problems and opportunities and think of new approaches to solve them, which may involve brainstorming, research, and experimentation. Students should also recognize the potential of their ideas and refine and develop them into viable solutions.

Creative thinking is essential for engineering students because it allows them to approach problems in new and innovative ways, come up with unique solutions to difficult problems, and create innovative products and services through engineering design. Furthermore, creative thinking helps students stay ahead of the competition and be more successful in their future careers.

Some argue that in a constantly changing society, success requires the development and mobilization of higher- order cognitive skills, rather than simply accumulating knowledge and understanding of a particular field [5]. However, it's worth considering how universities can effectively foster the development of these skills, which are essential for professional expertise in our society [6] [7]. Numerous studies have explored higher-order cognitive skills in the university context, with a particular focus on executive functions [8]. Executive functions are a set of cognitive processes that underpin critical and creative thinking. They help us plan, regulate, and monitor our behavior to achieve goals, and allow us to make decisions, problem solve, and think creatively. Key executive functions include working memory, cognitive flexibility, inhibition, and planning. These processes enable us to prioritize tasks, manage our time, and stay focused, and they are crucial for success in school, work, and life. Importantly, they require us to manipulate new information or prior knowledge to solve novel problems that cannot be solved through routine application of our existing knowledge [9]. Research has examined the development of executive functions among students from diverse academic disciplines, including social sciences and humanities, science and technology, and administrative sciences [10]. Students who demonstrate strong executive function skills are typically better equipped to solve complex problems [11].

However, many studies have focused on cognitive skills that are mobilized during assessments that involve the application of existing knowledge, rather than on the ability to solve open-ended or complex problems [12].

There appears to be a general consensus in the literature regarding the role of the didactic environment. A meta-analysis by [13] revealed that a mixed didactic approach, which integrates the teaching of disciplinary content with the encouragement of higher-order cognitive skill usage, produces greater effects than traditional pedagogical methods such as lectures. Additionally, research has shown that active learning activities, such as discussions, collaborative work, and project-based learning, promote the development of higher-order cognitive skills [14]. Behar-Horenstein and Niu [15] assert that instructors must have a good understanding of the higher-order cognitive skills relevant to their discipline and provide learning activities that are likely to develop them. While project-based learning is a common approach in engineering, used to develop disciplinary and transversal skills [16] (De los Rios, Cazorla, Diaz-Puente & Yague, 2010), few studies have examined the cognitive skills utilized by students in such contexts.

This research aims to contribute to the development of meaningful knowledge regarding higher-order cognitive skills in a university setting, specifically those that are relevant to complex problem-solving tasks. Our focus is on engineering education, and we seek to identify the higher-order cognitive skills employed during complex learning tasks, specifically the engineering design process.

II. CONCEPTUAL FRAMEWORK

A. Creativity in engineering

Creativity is an essential aspect of engineering that is crucial for developing innovative solutions to challenges that arise in the field [17]. The creative process in engineering involves identifying problems, brainstorming ideas, analyzing alternatives, and developing innovative solutions. This process requires innovative thinking and problem-solving skills. Creativity is vital in engineering as it enables engineers to generate successful solutions to complex problems. Creative problem-solving necessitates thinking outside the box and identifying multiple solutions to a given problem [18]. The creative process is iterative, with ideas being revised and refined over time, leading to more efficient and effective solutions.

Engineers must consider all possibilities and weigh the pros and cons of each option to determine the best course of action. Creative problem-solving also requires abstract thinking and visualization of how a solution will work in practice. Creative engineering involves developing new ideas and technologies [19]. Engineers must recognize opportunities to use existing technologies in new and innovative ways and come up with novel applications for existing technologies. Effective communication of complex ideas to others is also a part of creativity in engineering. Engineers must be able to convey their ideas in simple, easily understandable terms to others.

B. Taxonomies of cognitive processes

The taxonomy of cognitive processes developed by Benjamin Bloom and his colleagues in 1956 is undoubtedly the most widespread, and their contribution to the world of education has been considerable. It organizes cognitive activities into a six-level hierarchy, with the first three levels representing lower-order cognitive activities: memorization, comprehension and application. The top three levels represent higher-order cognitive activities: analysis, synthesis, and evaluation. More recently, [20] modified the terminology of this taxonomy by using verbs instead of common nouns to identify the levels, and by reversing the order of the two upper levels. The revised taxonomy reads as follows: 1) remember, 2) understand, 3) apply, 4) analyze, 5) evaluate, 6) create. This modification reinforces the idea that these are processes resulting from voluntary and intentional cognitive activity, which can be observed through students' achievements. Moreover, the revised taxonomy places the ability to create at the top of the hierarchy, recognizing its more complex, abstract and cognitively demanding nature. For example, creating a new model of any reality is more complex than evaluating an existing one.

However, not all members of the scientific community agree with this way of considering and organizing cognitive skills. As a result, the psycho-cognitive perspective [21] adds nuance to the model proposed by Krathwohl by stating that any type of thought has the potential to be of a higher order, depending on the structures underlying the activity. For example, the ability to remember, which is at the first rung of Krathwohl's Revised Taxonomy, may reflect the automation of knowledge and skills in response to a task that is made possible through many years of deliberate and indicative application of a mastery and an organized structure of knowledge [22]. Additionally, [23] show that all human cognition, whether it involves memorizing or solving complex problems, is based on two types of underlying knowledge structures: concept knowledge (also called declarative knowledge) and skill knowledge (also called procedural knowledge). What determines whether cognition is lower or higher order depends on the task to be performed and on the organization and cohesion of the network of subject-specific declarative or procedural knowledge structures that underlie the performance of the task [24].

More recently, [25] developed a taxonomy of higher- order cognitive skills that is divided into four broad categories, not mutually exclusive, and corresponding to four main cognitive activities: reasoning, evaluating evidence or arguments, problem solving and critical thinking, and finally, metacognition. These authors specify that for certain tasks, the degree of complexity may be such that they require the mobilization of all these skills. The ability to reason refers to both deductive and inductive reasoning. The researchers also examined heuristic reasoning, which refers to shortcuts or rules of thumb used to save time.

Regarding the ability to solve problems, several writings make a distinction between open problems (also referred to as complex, poorly structured, or ill- defined problems) and closed problems (or well-defined problems). The latter have a single correct solution and a generally well-established way to solve them. While open problems do not have a single solution or a clear or obvious way to solve them. This type of problem often requires making a judgment about the proposed solution. Moreover, for [26], a poorly structured problem requires the integration of various disciplinary knowledge. Mayer and Wittrock [27] add that experience in solving a certain family of problems also becomes a factor to consider. Thousands of hours of training and explicit practice are needed to develop true problem-solving expertise.

C. Problem-solving: differences between novices and experienced people

One way to clarify the development of the ability to solve complex problems is to compare learners based on the experience they have acquired in carrying out such tasks. This involves differentiating learners based on whether they are at the beginning of the program, and therefore novices, or whether they are more advanced in their progress and are considered experienced. However, it is important to note that the term “experienced” should not be confused with that of “expert”, which is generally used in a professional or legal context. Nor does is it refer to expertise as understood by specialists in the field (see [23]). The terms “novice” and “experienced” are simply used as opposite states to distinguish learners in terms of how they solve problems, based on their progress through the program. To do this, it is necessary to consider performance, which refers to the gestures and actions taken in a situation when solving complex problems. Taconis et al. [28], indicate that experienced people are able to complete tasks quickly and smoothly, without hesitation or errors, while continuously checking for possible errors.

The speed, ease and fluidity of the cognitive activity of experienced people contrast with the performance of novice people, which tends to be slower, hesitant and generally full of errors or faults. When it comes to solving complex problems, two dimensions can characterize the transition from novice to experienced: 1) from unstructured to structured and 2) from staged to automated performance. Thus, the performance of experienced people is highly structured, while it is unstructured in novices. Several authors have identified five characteristics present in experienced people that facilitate problem solving: possessing extensive knowledge of a domain, organizing it in a coherent structure, having a repertoire of problem-solving skills, automated problems, to devote more time to planning and to ensure effective follow-up of the problem-solving process [29] [22]. These characteristics explain why experts are faster, more efficient and show better thinking than novices.

The goal of this research is to identify the cognitive actions mobilized by students when carrying out complex tasks, particularly those related to engineering design. This skill remains one of the central skills of an engineer who is called upon to solve complex engineering problems by designing products or processes adapted to needs. Engineering design therefore involves the use of higher-order cognitive skills to creatively solve complex problems.

III. METHOD

The data for this research was collected through elicitation interviews with ten undergraduate engineering students. These interviews, which lasted approximately 45 minutes, were conducted in the weeks following the end of the winter 2022 semester. The aim of these interviews was to document the cognitive processes preferred by the students when carrying out complex learning tasks. The elicitation interview method, developed by [30] [31], aims to access dimensions of the experience of the action that are not immediately present in the person's consciousness, and to provide a detailed description of the accomplishment of a task or past activity.

According to [30], the elicitation interview is primarily aimed at verbalizing the action (both material and mental) as it is implemented in the performance of a specific task. The elicitation interview is an effective methodological technique for bringing to consciousness precious details of the implementation of the actions taken, such as "how did I do it?" and not just "what did I do?". The action is considered as a privileged source of information to understand the functional aspects of cognition, with the elicitation interview focusing on procedural aspects rather than conceptual ones. This technique allows the learner to become aware of the implicit dimension of their cognitive processes, which can be a key element of their learning.

Data analysis

The content analysis of the previously transcribed elicitation interviews was carried out according to [32]. His approach focuses on the manifest content and extracted units of meaning that enable the classification of cognitive processes used when carrying out complex learning tasks. A qualitative synthesis of these processes was then made.

Sample

The sample consists of five women and four men, aged between 19 and 22, who are enrolled in an undergraduate engineering program. Table 1 presents a summary of the respondents' profile, including their pseudonym, age, gender and the year and engineering program in which they are enrolled. We used a stratified sampling method, selecting students from each of the four years of the program. This sample allows us to detect possible differences between the cognitive processes used by beginners and advanced students. Other variables in the table can also help distinguish such differences. It is worth noting that the sample does not include representatives from all engineering programs offered at the institution where the research was conducted. However, after reviewing the program descriptions available on the institution's website, we found that the selected programs differ significantly in terms of the knowledge taught, the problems addressed and the intervention settings.

Pseudonyme	Age	Gender	Year	Programme
Hamed	19	Male	Freshman	Mechanical
François	19	Male	Freshman	Software
Celine	20	Female	Sophomore	Chemical
Mylene	20	Female	Sophomore	Chemical
Isabelle	20	Female	Sophomore	Industrial
Leila	21	Female	Junior	Civil
Stephane	22	Male	Junior	Geological
Sandrine	22	Female	Senior	Environmental
Charles	22	Male	Senior	Civil

The researcher invited participants for an individual interview that lasted a maximum of one hour. Participants gave their consent voluntarily. The researcher informed them about the research objective and the nature and conditions of their participation orally. The same data collection protocol was followed for all respondents to ensure uniformity in interview conditions. The interviews were conducted outside class periods to avoid academic constraints that may affect students, such as exams, coursework, or work to be submitted. Participants were asked to sit comfortably in a small room dedicated to teamwork. The researcher obtained permission to record the interviews on audio support.

Participants were reminded of the objective and theme of the interview, followed by the introductory sentence, "If you accept, I suggest that you take the time to choose a moment when you had to design." Afterward, the participants were given time to think and were asked to let the researcher know when they were ready to proceed.

The explicit interviews aimed to understand how respondents performed complex engineering design tasks. Participants were free to choose the design situation of their choice, provided that they had carried out the task themselves. Sometimes, the situation had to be changed during the elicitation interview, either because the respondent realized it was not a complex task or because a more relevant situation came to mind. In such cases, the researcher accepted the change, and the interview resumed with a focus on the new situation. This happened twice, once with Hamed and once with Celine. With Hamed, the researcher noticed that the situation he had initially evoked concerned a non-complex problem. With Celine, she preferred to change the situation a few minutes into the interview, indicating a higher level of involvement. Regardless, the chosen situation could have occurred at any point in the design process. All participants managed to find a situation that allowed them to explain their actions and were able to evoke and articulate their thought processes (i.e., embodied speech, [30]).

IV. RESULTS AND DISCUSSION

Most respondents chose to discuss a recent experience from one of their courses in the current study program. This was the case for François, Celine, Mylène, Isabelle, Leila, and Charles. Typically, these courses included an engineering design project. Since 2005, all undergraduate engineering programs at this institution require completion of a design project annually. Hamed and Sandrine chose to discuss situations they experienced during internships at companies, which have also been a compulsory training activity for all programs since 2005. The projects mentioned by respondents varied widely, likely due to differences in program specialization.

Despite the diverse projects and complex problems that the students faced, the analysis of the results revealed several commonalities in the mental operations mobilized at the start of the design process. These included clarifying the project's objective or purpose and building on prior knowledge or known data. Other cognitive processes, such as mental visualization and self-questioning, were shared by all respondents, although they may have occurred at different times in the design process.

We found few aspects that differentiate respondents when performing engineering design tasks. These aspects relate to the strategies of trial and error, as well as anticipating problems and predicting the consequences of choices. It should be noted that the variable that intersects with these aspects is the student's year of study, with a notable distinction between first- and second-year students compared to third- and fourth-year students.

A. Clarifying the objective or purpose of the project

A large majority of respondents indicate that one of the first mental operations when performing engineering design tasks is to clarify the objective or purpose of the project. This operation aims to ensure that they have understood the mandate entrusted to them and to specify the objective of the task in order to achieve a satisfactory result. The consideration of the objective also serves as the main criterion that will guide all other actions. Moreover, it is an essential element that always seems to remain present in the consciousness of the respondents. Analyzes and decisions flow from the interpretation made of the objective.

> "In design, what is hard? It is perhaps precisely the first stage, it is knowing what to find because you know, for example, we knew for that that it was the topography, but you know, we know that we're not just going to do a straight line and then we're going to take the mountains." (Charles)
>
> "Well, I ask myself again: Ok what is my mandate? What do I have to do? What information do I have that I dispose of? What is expected of me and in this

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context what will we necessarily have to find? I'm not going to get started if I don't have a guiding idea that tells me Ok with all this, I'm supposed to be able to do something." (Mylene)

The clarification of the objective of the task to be performed is a cognitive activity present among most respondents, which confirms the experts' opinions that the achievement of a desired result plays a vital role in the cognitive processes used in a situation of complex problem-solving [33] [34]. This consideration is particularly crucial when it comes to engineering design projects because the problem's issue is exacerbated in an authentic context or when dealing with a real client. In such cases, the credibility and reputation of the engineer, or the future engineer in the case of students, depend on it. Other factors also increase the pressure to understand the mandate to be carried out since the financial, human, environmental, and social costs associated with engineering design are often very high. Thus, the clarification of the objective helps reduce the likelihood of making erroneous decisions that could jeopardize the achievement of the desired goal. This behavior is consistent with Barron's work [35], which emphasizes the need to think critically when faced with a complex decision to resolve doubts about the best decision to make.

B. Building on prior knowledge or previous experience leads to creation

Several respondents indicated that they take stock of the knowledge acquired during their training, which could be useful to them in resolving the situation. This knowledge may correspond to theoretical notions in the field or to examples of similar problems solved in the past. This survey of knowledge or previous experiences, which occurs very early in the problem-solving process, seems, at first glance, to mobilize lower-order cognitive processes such as the location and retrieval of specific information from memory. However, since they are associated with a particular intention, in this case, comparing and looking for similarities to solve a problem, these processes would be considered higher order [24]. Indeed, the comparison and identification are done to identify elements in the acquired knowledge that could help solve the problem or to consider whether a known solution to a similar problem could be applied to the present problem. Thus, the recall of information occurs in a particular context, namely that of carrying out a complex task, by soliciting the cognitive structures where the knowledge that could be relevant to this situation is stored and organized [21]. With reference to the work of [35], the comments collected during the elicitation interviews allow us to deduce that the students use a process of inference to evaluate the possibilities and the evidence available in their memory that can be useful to them in achieving their goals.

"Well, when I had the subject all at once I automatically thought of my homework. I said to myself: "Ah, it's the same thing, I'll just have to do a copy-paste, change a few values and that's it. But once I really got into the assignment, I had to go a lot further than that… Which is to say, I had the basics for… that I had been shown in the other class, but I myself had to reflect and put in place a new method to solve the problem..." (Céline)

"So how do I tell myself I'm going to put this element there, this element there? Well, there... there when I draw I say to myself... I do it a lot from the knowledge I already have…so, there it is a bit in relation to the achievements that I have myself or common sense too that will make me tell myself that I will put things in such and such an order. (Mylene)

C. Decisions based on known data or strong constraints

Many students first consider the data available to them, which refers to the known elements of the situation. They take the time to gather factual information that is specific to the situation in order to take it into account when making decisions regarding the problem to be solved. This information can be crucial, as it highlights important characteristics of the project that may influence the choices. These characteristics can sometimes be strong constraints that make the situation complex and require students to find solutions to solve the problem.

"It's the first thing I do every time, I write what I actually know. The data I had to start my problem. I don't necessarily write them online, but I write them everywhere like words… Like, I have such data, I have such data…I write everywhere all the data I have to start my problem. (Mylene)

"…in this project it was the most difficult to position. So, since it was the most difficult, it was the one who asked us the most constraints, you couldn't place it anywhere. So it was the one we placed first. Because if it didn't work for it, the rest didn't work." (Steve)

Constraints are a particularly critical aspect of engineering design. They represent all the obligations that need to be met to ensure that the proposed solution can fulfill the various functions for which it is designed. The nature of the constraints is varied, and they can relate to operation, safety, ergonomics, aesthetics, cost, sustainable development, or any other element imposed by the specifications. The specifications can sometimes impose a large number of constraints. In the context of engineering education, constraints related to a design project lead students to consider them in order to create a relevant solution. This consideration can instigate the ability to reason, which is one of the four higher-order cognitive skills proposed by [25]. The reasoning in this case is done by evaluating the preponderance of the criteria associated with the design project. These criteria reveal constraints which in turn influence decisions. Moreover, the constraints encourage students to consider the particular conditions of each situation. In connection with the work of [21], who proposed two types of structures underlying knowledge, it seems necessary to add a third type of structure which refers to conditional knowledge. This type of knowledge is generally not the subject of explicit teaching in engineering education. However, we note that it is an essential aspect to develop for solving complex problems.

D. Mental visualization

Most respondents frequently mention mental visualization, which refers to the ability to mentally represent a situation through imagination. Mental visualization is a cognitive process that can occur consciously or unconsciously, and it can be used in various contexts, including sports, business, work, or study. In this context, mental visualization is used consciously and deliberately and appears to support other higher-order cognitive processes, such as analyzing mental representations or evaluating possible decisions.

Mental visualization takes different forms and expresses itself in different ways. Some individuals visualize sequentially, while others visualize globally, and some can even vary the focal length (zoom) on specific aspects of the mental image. Another important aspect of mental visualization is the point of view of the person generating the mental representation. The point of view can be internal, where the respondent sees the mental image directly, or external, where the respondents observe themselves seeing the mental image.

> "So, once I had that data, what I started doing was really imagining what blocks of equipment I'm going to need to add myself to be able to do something functional. It is the drawing this time that I study, that I look at. And I try to imagine what is it that I have to add now to be able to have a loop that looks like something good." (Mylene)

> "I walk under the pillar. Because me what I'm looking for is my river and the pillars are there, me what I'm seeing, now that the river isn't full of course, I'm moving below the pillars of the bridge and I watch. And I watch. That's what I do." (Sandrine)

> "So that I launch a first direction then I look: oh no there it doesn't work there, oh no there here we will say there were too many rocks it is sure that we did not pass by there. There you throw… You make an imaginary path. Ok, let's say, I'll go through it, I'll go through it." (Charles)

E. Self-questioning

All participants in the sample use self-questioning, which refers to the ability to ask questions to oneself, as a method during the design process. It can be expressed out loud or internally. The use of questioning has two main motivations. Firstly, it serves as cognitive scaffolding to follow a procedure. The questions function as a guide to ensure that procedural knowledge is valid [21]. Secondly, it provokes reflection on the consequences of decisions. This less frequent but equally useful reason involves asking questions that infer the possible outcomes of decisions [35]. Both reasons align with higher-order executive functions that regulate thought and behavior.

> "…I try to do, to tell myself what the stages were for the construction. I try to say to myself: "ah, is this going to work? Is this going to be complicated? Am I as well finding other things? If I take this option will it work?" (Isabelle)

> "…I read it, I re-read it and then I re-read it again until I know all the equations. Until I really really know the subject and there I started to ask myself certain questions to guide me towards the process... Well, where I was blocking, I said to myself: "ok". I asked myself the question: "Well there I am blocking. How do I do this? What am I missing?" (Mylene)

F. Aspects that differ

The analysis of the elicitation interviews has enabled the identification of some distinctive aspects that differentiate respondents with regard to the cognitive processes employed during the performance of complex tasks. It is worth noting, however, that this differentiation is solely attributed to the contextual variable of the year of study. The other sociodemographic variables, such as gender, age, or study program, do not seem to play a discriminatory role, at least in terms of the cognitive processes mobilized by students. These aspects refer to the strategies of trial and error, as well as anticipation of problems and forecasting the consequences of choices.

G. Trial and error

First- and second-year students appear to use the trial-and-error strategy more frequently than third- and fourth-year students, which may indicate gaps in their declarative, procedural, or conditional knowledge [21]. It may also suggest a gap in the development of certain higher-order cognitive processes, to the advantage of more experienced students [28]. Since novices have a more limited repertoire of automated problem-solving skills [29] [22], they are likely to resort to the trial-and-error strategy to gradually enrich their knowledge and experience inventory for later use or reference. Over time, the cumulative errors observed and corrected by learners affect their knowledge structuring process, leading to a more effective problem-solving capacity.

> " Yes. Lots of trial and error during the project. For the values it is very arbitrary. So, we figure the maximum value is 255 so… then it's like, ok that, it must be like 75% power, we'll try that. Sometimes it was 5.0, it really wasn't enough, we're going to try 7.5" (François)

> "…I continue other iterations. I went to see the fluids. I started to change the temperatures a bit to see how it varied in my results. So, I played around with the temperatures a bit and what settings I could tweak to see how it affected my heat exchanger. But I saw that it wasn't becoming... it wasn't getting any better there... Maybe a little, but not that much. (Hamed)

"So here I am trying to find a solution, etc., but I am fumbling a lot and I go back a lot. I also say to myself a lot: "but was it true… was it really…? ". So it's very much a process of: I go back; I question a little what I have just said to myself and then afterwards I take a step forward, but I grope a lot to arrive at a solution. (Mylene)

H. Anticipating problems and predicting the consequences of choices

Respondents tend to think ahead to anticipate problems relating to their concept design. This anticipation influences their thinking and choice. On the other hand, beginning students have more difficulty foreseeing the undesirable consequences of their choices. This concern is more present in the discourse of respondents who are in the third or fourth year of the program.

"I think it's just more experience, because we didn't know that it would have been a problem. […] It's really difficult to be able to, like, foresee certain problems that could arise, but we say to ourselves, this is the ideal process so what would be the parts of the program that we will need?" (Francis)

"I wasn't aware from the start because I was changing the temperature, but I was forgetting to redo my density calculations and all that so by changing the temperature I was changing the necessary heat exchange, but the properties of my fluids weren't changing. So that's an error that I noticed later in the project where I said: "wait a minute, I didn't change these parameters so..." (Hamed)

Indeed, more advanced students in the program stand out from beginners due to their ability to anticipate the consequences of their choices. They rely on their knowledge to extrapolate possible outcomes based on different imagined scenarios. This sub construction process seems consistent with the work of [35], who emphasizes the importance of judgment when evaluating possible scenarios with regard to the achievement of goals. This cognitive process is similar to the cognitive strategy of metacognition as proposed by [36], but with the difference that it is carried out a priori, that is to say, before the execution of tasks. It would then be more appropriate to refer to it as precognition, a preliminary step in the succession of cognitive processes in a situation of complex problem-solving.

"The first ones were easier because I went with those that I know I don't want to put my powerhouse there. The ones that I'm 100% sure of, that I say: there's no point trying to put it there. Then after that there it is in: humm maybe yes here, there what is the most important? Am I neglecting the environment or am I neglecting it? Which is what I prioritize in the end. What is best for the plant? " (Leila)

"It's really just kind of a design draft of the…it's not really modeling because there aren't really any numbers coming out yet, just primary calculations being done. . And then we have not yet applied the thermodynamic model behind it. We thought about it, but I only apply it there and then I realize if it works or if it really doesn't make sense to do it. (Stephane)

"I am trying to find out what the problems would be at this level. Like a little bit like: I wouldn't want this problem to happen, I wouldn't want construction problems to happen in general, so I say good: "what could happen as a problem. Can I try to fix them right away by changing parts? (Isabelle)

"So, I try to actually imagine the flaws in the design that I did. And what could make it actually not work. (Mylene)

V. CONCLUSION

The present study aimed to investigate the impact of project-based learning on creative complex problem-solving and higher-order thinking skills among undergraduate engineering students. Engineering programs strive to produce graduates capable of solving complex problems [2], which often require the deployment of higher-order cognitive skills such as analysis, evaluation, critical and creative thinking [3]. The study utilized elicitation interviews conducted with nine undergraduate engineering students to identify the cognitive skills utilized during the engineering design process to solve complex problems. The findings suggest that the implementation of active pedagogies, including project-based learning, which expose students to complex problems, promotes the utilization of higher-order cognitive processes, supporting the conclusions of prior research [13]. Furthermore, the fact that many of these processes were common among all participants indicates that the teaching environment can influence the selection of cognitive processes, which results from a voluntary and deliberate action, consistent with [20]'s taxonomy of cognitive processes.

Furthermore, the observation of certain differences in the cognitive processes employed by the students, depending on their level of expertise, indicates the evolutionary nature of these processes and suggests that they can be developed through formal university training. However, it is unclear whether students exclusively developed these cognitive processes through their participation in the engineering design process, without direct instruction. It would be relevant to test this hypothesis, as several experts argue that explicit teaching of cognitive processes is necessary for students to develop them [11] [21].

Also, the analysis of the comments gathered from the respondents of this sample indicates that cognitive processes can be superimposed, taking place simultaneously, as suggested by [35]. However, the observed simultaneity reveals a complementary dynamic that seems to alter the nature of cognitive processes, which could otherwise be considered lower order. This finding is important as it is consistent with the psycho-cognitive perspective, particularly the work of [21] [22], who categorize cognitive actions according to the structures underlying the carried- out activity.

Although the findings of this study support the notion that higher-order cognitive processes play an important role in creative complex problem-solving, there are some limitations that should be noted. Firstly, the sample size used in this study was relatively small, and the results may not be generalizable to larger populations. Secondly, the study did not include a measure of student motivation, which could have provided additional insight into the effects of project-based learning on creative problem-solving. Future research should investigate the effects of project-based learning in different contexts, as well as the potential mediating role of motivation. Additionally, research should explore the long-term effects of project-based learning.

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