Education 4.0 Supporting Remote, Hybrid, and Face-to-Face Teaching-Learning Systems for Academic Continuity during the COVID-19 Global Pandemic

The Mechatronic Product Design Course in Higher Education as Case Study

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***Abstract*—The COVID-19 global pandemic provoked the emergence of new teaching-learning systems necessary to guarantee academic continuity at all levels, resulting in remote, hybrid, and face-to-face teaching-learning processes becoming more robust and efficient. However, higher education faces a significant challenge because, in many cases, the physical infrastructure with face-to-face access to specialized laboratories must have integrated, functional, and practical learning to train disciplinary competencies. Consequently, it is required to implement new pedagogical procedures and remote technologies to compensate for the lack of face-to-face access to laboratories. This study examines Education 4.0, the intersection of technology and pedagogy in today's higher education landscape. A case study is presented to provide a comprehensive comparison of remote, hybrid, and face-to-face learning modalities, illustrating their unique features and effectiveness in different educational contexts.**

Keywords-Education 4.0; Higher Education; Educational Innovation; Engineering Education.

I. INTRODUCTION

The global pandemic caused by the coronavirus (SARS-CoV-2) has resulted in the most significant health crisis of the modern era, causing social and economic devastation worldwide. One of the most affected sectors was education at all levels. During 2020 and 2021, face-to-face academic activities were suspended worldwide due to prevention and mitigation measures to contain the spread of the virus. For several months, the uncertainty and prolongation of the health crisis forced educational institutions to develop various short, medium, and long-term solutions that incorporated new pedagogical models, learning methods, delivery modalities, and teaching-learning programs powered by 4.0 technologies. These solutions aimed to guarantee academic continuity at all levels and make remote teaching-learning processes more robust and efficient. In 2021 and 2022, the return to face-to-face instruction occurred mainly in hybrid and face-to-face teaching-learning modalities. However, the courses had to be flexible enough to adapt to the possibility of returning to a remote education format at any time. These activities were accompanied by implementing safety measures such as mask-wearing, social distancing, best practices, and knowledge gained during the crisis.

During academic continuity efforts amidst the pandemic, various challenges arose, including infrastructure issues such as access to platforms and devices, stable electricity and connectivity, training stakeholders in Information and Communication Technologies (ICTs), and designing new pedagogical procedures to maintain student engagement and assess their knowledge effectively. Higher education faced unique difficulties, particularly with face-to-face access to specialized labs needed for practical learning and developing disciplinary competencies. To address these challenges, the educational sector embraced Education 4.0, a combination of technological advancements and pedagogical procedures [1].

The implementation of existing and emerging ICTs, including virtual classrooms, virtual labs, and remote labs, played a vital role during the pandemic. Studies showed that students could learn and develop disciplinary competencies with favorable outcomes using these technologies [2][3]. Virtual laboratories utilized traditional multimedia resources, 2D simulations, and immersive 3D environments, incorporating Virtual Reality (VR) and Augmented Reality (AR) techniques. Successful examples of these technologies were seen in teaching basic sciences, such as physics, chemistry, and mathematics [4][5].

In higher education, VR and AR have also been observed in various implementations, for instance, during the design process and development of technology-based products. Furthermore, the combination of virtual environments with hardware systems employing haptics and joysticks has made the learning experience highly relevant, as students can combine tactile sensations, vision, and proprioception during their learning process. Examples can be observed in physics [6], medicine [7], and engineering [8], among others. Most recently, the integration into higher education of Natural Language Processing (NLP) systems based on Artificial Intelligence (AI), such as those developed by the OpenAI company, has the potential to significantly improve the efficiency of tasks, such as grading and content creation [9].

In the case of engineering education programs, the use of Learning Management Systems (LMSs) has enhanced their capabilities to provide access to specialized virtual laboratories in engineering. For example, specific features have been included to support Computer-Aided Design, Manufacturing, and Engineering Systems (CAD, CAM, CAE) and other more complex and robust systems, including Product Lifecycle Management (PLM) software and

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Supervisory Control and Data Acquisition (SCADA) systems [10]. Also, Engineering Education has implemented simulations of manufacturing plants and industrial robotics, the latter using software for simulating discrete events and digital twins' techniques [11].

On the other hand, remote laboratories have grown exponentially due to technological advances in communication and connectivity. Today, Cyber-Physical Systems (CPS) laboratories are a type of laboratory where physical elements and software components intricately intertwine. Remote laboratories allow the experience of telepresence in physical laboratories, carrying out practices and remote experiments with actual equipment with the advantages of flexibility in time and place [12].

This work uses the concept of Education 4.0 to design new teaching-learning systems and pedagogical procedures, with a case study on the "Mechatronic Product Design" course demonstrating the application of ICTs and learning methods for remote, hybrid, and face-to-face dynamics.

The rest of this paper is structured as follows: Section 2 introduces the concept of Education 4.0. In Section 3, the Education 4.0 Reference Framework is presented as a conceptual foundation for designing teaching-learning systems in higher education. Section 4 provides a case study illustrating the design, development, and implementation of a new teaching-learning system within the context of Education 4.0, using the "Mechatronic Product Design" course as an example. Finally, conclusions are drawn in Section 5.

II. EDUCATION 4.0 IN HIGHER EDUCATION

The Education 4.0 concept has been implemented in various contexts and described by different authors. Therefore, the education sector has been evolving and leveraging particular technologies of the fourth industrial revolution, such as generic technology for connectivity, datafication, digitalization, smartification, and virtualization. The combination of these technologies with active learning methods and professional instruction to train key competencies in students today is known as Education 4.0. Also, Education 4.0 can refer to the training and development of core competencies in engineering education for Industry 4.0 [13], according to the Education 4.0 Framework proposed by the World Economic Forum. The Education 4.0 framework is characterized by critical shifts in learning content, the development of essential skills and competencies, and experiences to redefine quality learning in the new economy [14]. In addition, the fostering of self-learning (heutagogy), collaboration (peeragogy), and the highlighted use of ICTs (cybergogy) is included in Education 4.0.

This work considers the use of 4.0 Technologies with current techniques and methods in education for the development of desirable competencies in the profile of today's students. We use the following concept of Education 4.0 applied to higher education as a reference: "Education 4.0 is the period in which the education sector takes advantage of emerging ICTs to improve pedagogical processes that are complemented by new learning methods and innovative didactic and management tools, as well as smart and sustainable infrastructure used during current teaching-learning processes for the training and development of key competencies in today's students" [1].

Therefore, identifying the key enablers to achieve the Education 4.0 vision is crucial to guide educators during teaching-learning. Additionally, designers, researchers, and specialists in teaching-learning programs and instructional design should refer to these key enablers.

Six categories of key enablers are used in the design and implementation of today's teaching-learning systems, and Figure 1 summarizes the key enablers of Education 4.0 [15].

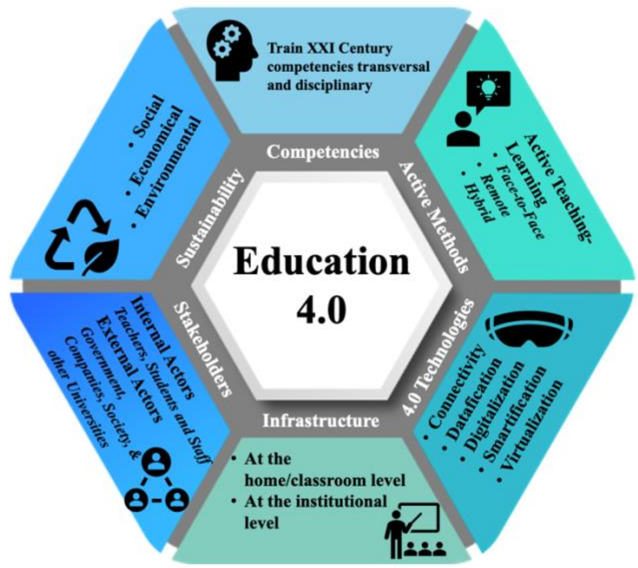

Figure 1. Six key enablers of Education 4.0, adapted from [15].

1) Training key competencies, covering both soft and hard competencies for students.

2) Applying active teaching-learning methods with various modalities, such as problem-based learning, project-based learning, experiential learning, and gamified learning.

3) Utilizing 4.0 Technologies, which involve connectivity, datafication, digitalization, smartification, and virtualization.

4) Implementing innovative infrastructure, including services, facilities, devices, and physical-virtual environments to enhance teaching-learning processes.

5) Involving relevant stakeholders, such as internal actors (teachers, students, staff) and external actors (government, industry, society, other universities) in the teaching process.

6) Considering sustainable impacts by aligning with the UN Sustainable Development Goals (SDG) to create positive social, economic, and environmental effects.

III. THE EDUCATION 4.0 REFERENCE FRAMEWORK FOR DESIGNING TEACHING-LEARNING SYSTEMS

The Education 4.0 Reference Framework for designing teaching-learning systems was used in this work [15]. This reference framework allows designers to be guided during the design and development processes of new educational products, teaching-learning processes, and educational infrastructure, considering the concept and vision of Education 4.0.

This reference framework is justified by the need to create integrated systems where product, process, and infrastructure interact for improved performance. Additionally, these systems must adapt to existing contexts and environments while considering the key enablers of Education 4.0. The reference framework incorporates the six key enablers of Education 4.0, enabling resources to support training in transversal and disciplinary competencies through active teaching-learning processes in various delivery modes (face-to-face, hybrid, remote). This innovative infrastructure, with the participation of key stakeholders and the support of 4.0 Technologies, facilitates positive social, economic, and environmental benefits. It is, therefore, necessary to have an integrative vision that can offer a new education product, a new teaching-learning process, and the necessary infrastructure to achieve more efficient and effective processes and a better user experience. Although this framework allows an integrated design (product-process-infrastructure), it can also facilitate the design process for individual entities, as presented in the case study section for the design of a "teaching-learning process."

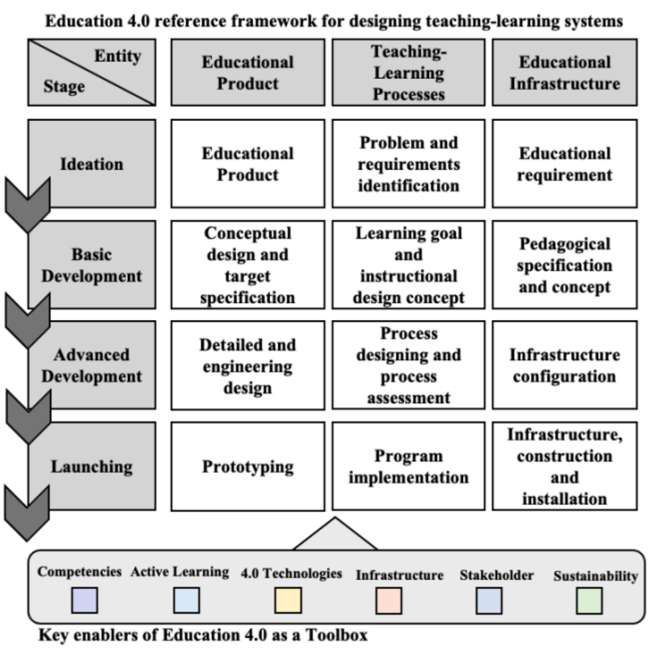

Figure 2. The Education 4.0 reference framework for designing teaching-learning systems.

This reference framework comprises four design stages of the product development lifecycle in a systematic design process: (i) Ideation, (ii) Basic development, (iii) Advanced Development, and (iv) Launching. Figure 2 presents the general model of the Education 4.0 Reference Framework for designing teaching-learning systems.

IV. Case Study: The Mechatronic Product Design Course in Higher Education

Innovation and entrepreneurship among today's students lead to creative, efficient, and practical solutions to society's challenges and problems and achieving sustainable goals. However, the current social context, technological advances, necessary processes of digital transformation, and new paradigms in education bring challenging teaching-learning scenarios for educators. The lack of specialized guides and resources to address these challenges is a current problem. In addition, engaging and motivating students in current teaching-learning processes is necessary. Consequently, efficiently teaching and inspiring the next generation of students/entrepreneurs is challenging for educational institutions. Therefore, access to high-quality, innovative, and affordable teaching-learning systems is needed to contribute to forming highly competitive professionals.

The course "Mechatronic Product Design" is presented as a case study to illustrate the design, development, and implementation of new teaching-learning systems in Education 4.0 to design teaching-learning processes. This course is among the academic offerings in the mechatronics engineering and mechanical engineering careers at Tecnologico de Monterrey in Mexico. Implementing this course was justified as part of the emerging programs to ensure academic continuity in this institution during the 2020 - 2022 global health crisis.

Tecnologico de Monterrey implemented a strategy to redesign its face-to-face courses in a remote-hybrid format applying a flexible-digital model [16]. Online resources and 4.0 Technologies were primarily implemented to carry out this transformation. Also, national and multi-campus courses were opened to optimize resource use and leverage the benefits of distance formats. Therefore, students attending the 26 Tec campuses in Mexico enrolled in these courses.

In engineering education, teaching-learning processes require physical infrastructures, including specialized laboratories and tools, because they are necessary for training disciplinary skills/competencies and experiential and practical learning.

Mechatronic engineering was a challenging area because it encompasses various disciplines such as mechanics, software, electronics, and control systems and is also one of the engineering areas most impacting industry thanks to the implementation of emerging technologies in new products and the generation of best practices in current production systems.

In addition, the emergence of smart and sustainable products and processes has assumed significant relevance in recent years. That is why holistic designs of new products, manufacturing processes, and production systems are necessary for mechatronics. Therefore, distance teaching and practical activities in this field have become challenging.

The Education 4.0 Reference Framework for designing teaching-learning systems was taken in this work's redesign process, and particular requirements were considered. In addition, the four stages of transformation from traditional courses (face-to-face) to online distance "remote" and "hybrid" courses (flexible-digital) as part of the program designing activities were also used: (i) planning, (ii) synchronous elements, (iii) asynchronous elements, and (iv) preparation for delivery. Figure 3 summarizes the four implemented stages during the transformation process. Table I summarizes the application of the four design stages of the Education 4.0 Reference Framework for designing teaching-learning systems. Table II presents the teaching-learning process, highlighting how the Education 4.0 enablers shaped the "Mechatronic Product Design."

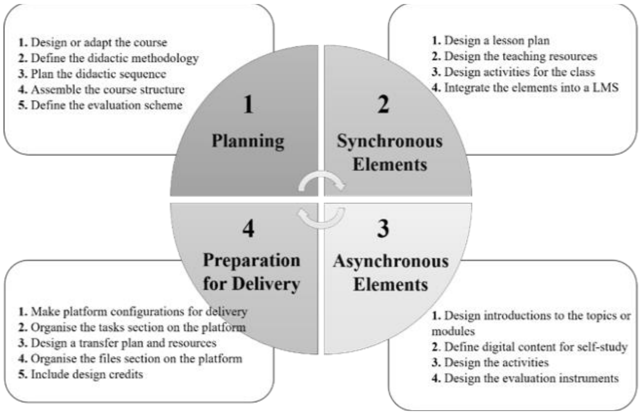

Figure 3. The transformation model from traditional courses to remote and hybrid courses.

TABLE I. SUMMARY OF THE DESIGN PROCESS, TEACHING-LEARNING PROCESS ENTITY

#	Activities	Particular Model
1	***Problem and Requirement identification specification***	**Problem:** Redesign the "Mechatronic Product Design" course from face-to-face to remote and hybrid delivery modalities and provide adequate training and development of key transversal and disciplinary competencies considering experiential and practical learning as core issues. **Student profile:** Undergraduate Mechatronics Engineering and Mechanical Engineering students at Tecnologico de Monterrey, Mexico. **Semester:** 8 or 9. **Previous knowledge:** Embedded systems, computerized control, and machine analysis and synthesis. **Duration:** 22 sessions (2 hours per session), 44 hours for summer sessions. And 16 sessions (3 hours per session), 48 hours for a semester session. **Delivery Modality Goal:** Remote (synchronous and asynchronous) and Hybrid. **Academic periods to be implemented:** Summer courses and Semestral courses.
2	***Learning goals definition and instructional design concept***	**Learning Outcomes:** At the end of this program, participants learn best practices and apply the appropriate tools of technology-based and mechatronic product, process, and manufacturing systems designs, create working prototypes, identify market segments, and define business models and manufacturing systems.
3	***Process designing and process assessment. Program assessment***	**Process designing:** Application of the transformation model from traditional courses to remote and hybrid courses: (i) Planning, (ii) Synchronous elements, (iii) Asynchronous elements, and (iv) Preparation for delivery. **Assessment Instrument:** The "i-Scale" was implemented [17]. This tool covers qualitative evaluations for learning outcomes, the nature of innovation, growth potential, institutional alignment, and financial viability. This evaluation indicated that this course has few or no drawbacks to be implemented.

6	***Program implementation***	**The number of students and delivery modality:** 28 students from 7 campuses across Mexico (Summer 2020, Remote). 56 students from 2 campuses in the Central Mexico region (February-June 2021, Hybrid and Flexible). 50 students from 2 campuses in the Central Mexico region (February-June 2022, Face-To-Face and Flexible). **Students' assessment method:** Mixed method analysis applying surveys about the perception of the transversal competencies trained and a qualitative evaluation of the working prototypes. **Research question for quantitative analysis:** What is the student's perception of the training of transversal competencies in these courses? **Research question for qualitative analysis:** What are the results of developing mechatronic working prototypes in these courses?

TABLE II. THE MECHATRONIC PRODUCT DESIGN COURSE CONSIDERING THE EDUCATION 4.0 ENABLERS

Modules	Education 4.0 Enablers	Goal
1. Introduction to innovation and new product and process design Key concepts related to innovation and methodologies for new product and process design and development.	**Main Competencies:** *Soft: Critical Thinking; Hard: Methodologies Design* **Main Active Methods:** *Active Learning and Flipped classroom* **Main 4.0 Technologies:** *LMS, Web-conference platform, and instant message systems.* **Main Infrastructure:** *At institutional, access to remote labs and virtual classrooms* *At home, connected and connectivity services* **Main Stakeholders:** *At least two teachers were involved* **Sustainability:** *SDGs were promoted*	• Identify types and sources of innovation. • Identify the methodolog y and techniques to be used.
2. Mechatronic Product Design Design and development of a mechatronic product through four stages: (i) Conceptual design, (ii) System design, (iii) Engineering and detailed design, and (iv) Prototyping and validation.	**Main Competencies:** *Soft: Collaboration, Cooperation, Creativity & Innovation.* *Hard: Mechatronic principles and integrated product design* **Main Active Method:** *Blended-based Learning and Learning by Doing* **Main 4.0 Technologies:** *LMS, Virtual labs for simulation, and 3D modeling systems* **Main Infrastructure:** *At the institution, access to physical and remote labs and virtual classrooms* *At home, connected and connectivity services* **Main Stakeholders:** *At least two teachers and one specialist from the industry were involved* **Sustainability:** *Design for Sustainability (DfS) and Life Cycle Assessment (LCA)*	• Identifying opportunity areas • Understandi ng painful situations and customer/us er requirement s. • A prototype of the proposed mechatronic product. • Evaluation of the mechatronic working prototype.
3. Manufacturing Process Design	**Main Competencies:** *Soft: Collaboration, Critical Thinking.*	• Definition of materials

Design and development of a manufacturing process through three stages: (i) Conceptual design, (ii) Technology selection, (iii) Production Plan.	*Hard: Process Design, Production Scheduling, and Virtual Commissioning.* **Main Active Method:** *Blended-based Learning and Learning by Doing* **Main 4.0 Technology:** *Spreadsheets, Software for Plant Design, Project Management, and Plant Simulation* **Main Infrastructure:** *At institutional, access to remote labs and virtual classrooms.* *At home, connected and connectivity services.* **Main Stakeholders:** *At least two teachers and one specialist from the industry are involved.* **Sustainability:** *Design for Sustainability (DfS) and Life Cycle Assessment (LCA)*	and processes to be used. • Organization of the plant and schedule of activities. • Analysis of main costs and projected sales.
4. Business Model and Launching Define and validate the value proposition of the product/process/business and product pitch.	**Main Competencies:** *Soft: Communication.* *Hard: Enterprise creation and marketing principles* **Main Active Method:** *Blended-based Learning and Learning by Doing.* **Main 4.0 Technology:** *LMS, Virtual Classroom, and Collaborative Virtual Platforms.* **Main Infrastructure:** *At institutional, access to remote labs and virtual classrooms.* *At home, connected and connectivity services.* **Main Stakeholders:** *At least two teachers and one specialist from the industry are involved.* **Sustainability:** *Business sustainability assessment (short-medium-long term).*	• Product market-fit • Product pitch • Product business model

Building upon the Education 4.0 concept, this study utilizes the Education 4.0 Reference Framework to design teaching-learning systems that cater to the evolving needs of the education sector. By incorporating the four stages of transformation (planning, synchronous elements, asynchronous elements, and preparation for delivery), this research effectively adapts traditional face-to-face courses to the online distance "remote" and "hybrid" formats, which are better aligned with the flexible-digital approach in Education 4.0.

Figure 4 presents the results of an applied survey about the perception of the trained transversal (soft) competencies during the impartation of this course. The graphics compare both surveys, a pre-survey based on the perception of how often these competencies are trained during their classes and a post-survey based on the perception of how often the competencies were trained during the boot camp. These surveys were applied during three periods (2020, 2021, and 2022) to analyze how the three different delivery modalities impacted the designed course. The presented results show that most of the students perceived that the promoted key competencies were trained during the activities of this course. Figure 4 shows a significant increase in the feeling of accomplishment of the students regarding the soft competencies that were designed and implemented in the course. Additionally, general satisfaction with the course experience was positive in 75% of the cases.

Also, in this course, the students were encouraged to develop collaborative and cooperative mechatronic projects; then, group activities were promoted, and teams were formed. For the case of the remote course, the teams were integrated by students from different campuses; for hybrid and face-to-face, the teams comprised students from different areas in the mechatronics and mechanics fields. Therefore, the formed teams allowed students to propose various new mechatronics products and their manufacturing processes and business models. These products aimed to address current social needs, pursue sustainability, and follow technological megatrends to be updated and remain competitive in the marketplace.

For this study, 16 new mechatronic products were evaluated. The projects presented corresponded to 3D models accompanied by simulations, Apps, and in some cases, rapid prototyping through 3D printing methods and rapid prototyping with Arduino boards. It was possible for the three formats (face-to-face, hybrid, remote) thanks to the provision of physical and virtual infrastructure at both levels, institutional and home. The positive results obtained highlight the potential of these new teaching-learning systems and modalities in fostering essential skills and competencies required for the new economy.

V. CONCLUSIONS

Due to global lockdowns resulting from the COVID-19 pandemic, institutions have rapidly transitioned to digital education models, supported by diverse ICTs, leading to the emergence of Education 4.0. Through this paper, a framework for designing courses within the context of Education 4.0 is presented.

The framework introduced is explained with a case study of an engineering course involving the process and design of a mechatronic product. This course was chosen as a practical example of implementing a highly complex course on multi-campuses and surveying students in the same major but with different educative backgrounds. Moreover, the course format facilitated interaction among students from different campuses and disciplines, creating active learning environments with synchronous and asynchronous teamwork activities.

Throughout the three different delivery modalities (face-to-face, hybrid, remote), the course demonstrated adaptability and flexibility in response to varying circumstances. The consistent positive outcomes across modalities indicate that the Education 4.0 framework is robust enough to accommodate diverse teaching and learning needs while maintaining high-quality education.

The results showed that aligning the learning goals with the key competencies to be trained and applying correct learning methods supported by adequate ICTs of 4.0 Technologies and infrastructure made it possible to generate product ideas and conceptual products and create physical and working prototypes. It demonstrated that students could implement the acquired knowledge and integrate core concepts in this engineering area. Likewise, this new class format allowed students to interact with others from different campuses and disciplines and generate active learning environments with synchronous and asynchronous teamwork activities.

Finally, this paper encourages further investigation of the Education 4.0 framework across various disciplines, levels, and cultural contexts. By examining the framework in diverse environments, researchers and educators can enhance understanding of its potential and limitations, ultimately guiding best practices and policies for future teaching and learning.

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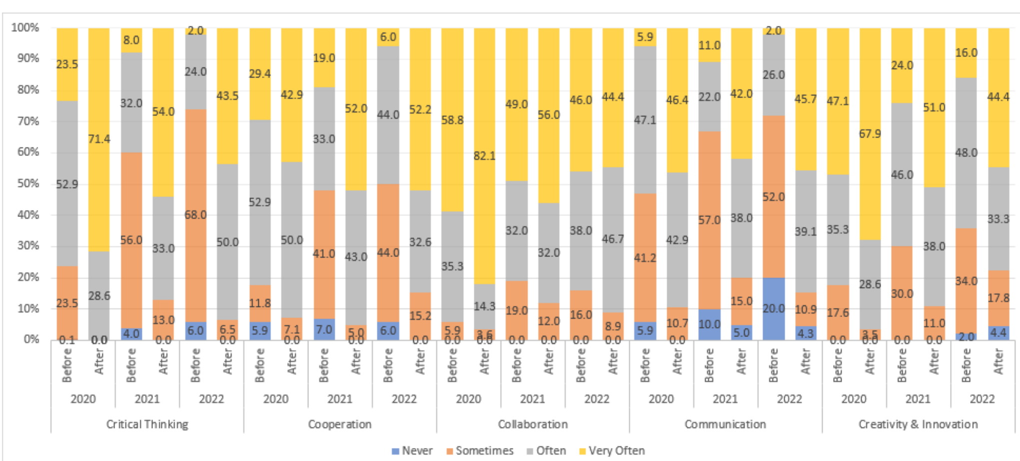

Figure 4. Survey results comparing the key transversal competencies trained before and after the course (2020 – 2021 - 2022).