Transdisciplinarity as a Learning Challenge: Student Experiences and Outcomes in an Innovative Course on Wearable and Collaborative Robotics

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Abstract*—*Contribution: **This study provides evidence for the benefit of short online courses for the transdisciplinary competence development of graduate students. It shows the significant challenges students face while learning, and provides instructional recommendations to improve students' learning quality and professionalism.**

Background: **Developing wearable and collaborative robots require industry collaboration and transdisciplinary competence. Industry's involvement in long-term programs is becoming infeasible, and the nature of transdisciplinary learning has not been explored to inform instructional practices.**

Intended Outcomes: **This study aimed to provide instructional recommendations based on an in-depth examination of a diverse group of graduate students' learning and teamwork experiences as well as outcomes in a 5-day online transdisciplinary course.**

Application Design: **Thirty-one graduate students of engineering, industrial design, and health fields from four countries participated in online mixed-discipline instructional sessions and teams to address a real industry challenge. A mixed-methods approach was used to examine students' experiences and learning outcomes based on a competence measure, session participation data, student journal entries, team progress reports, team elaboration visuals, and final team presentations.**

Findings: **Students' knowledge of industrial design, medical considerations, ethics and standards, effective teamwork, and self-regulated learning were increased. Students' high motivation helped them deal with the challenges involved. Daily student journals, team reports, and visual elaboration tools were found to be beneficial for determining the challenges and learning quality. The observed student progress within five days is promising, making it worthwhile to further explore the benefits of short online courses for increasing graduates' readiness and establishing university-industry collaborations in education.**

***Index Terms*—Challenge-based instruction, graduate students, industry partnership, self-regulated learning, skills gap, synthesizing, teamwork, transdisciplinary.**

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I. Introduction

WEARABLE and collaborative robotics tackles important societal challenges, such as improving the working conditions of human–robot shared manufacturing environments (e.g., [1], [2], [3], and [4]), and supporting health and well-being of individuals in need (e.g., [5], [6], and [7]). Developing these technological solutions requires extensive knowledge of human behavior and related design methodologies (e.g., [8], [9], [10], and [11]). Meeting the increased demand for wearable and collaborative robots is "expected through the integration of diverse fundamental technical expertise and by developing cross-domain cooperation" [12, p. 165]. Unfortunately, there is a global shortage of talent referred to as "the skills gap"—which hinders technological development in all areas [13]. A recent report showed how underprepared the engineering graduates felt for the workforce: 59% felt ready for the required curiosity and persistent desire for continuous learning, 55% felt ready for identifying, formulating, and solving engineering problems, 49% felt ready for the required communications, 31% felt ready for teamwork and multidisciplinary work, and only 17% felt ready for project management [14]. Considering the market demand, advancing education in the field of wearable and collaborative robotics is of critical importance. There is a need for relevant transdisciplinary competence, and studies addressing this issue with in-depth analyses of learners' needs to offer effective instructional strategies and tools.

The literature on "innovative" ways to increase graduates' readiness can be used as a guide for instructional explorations to effectively develop transdisciplinary competence. The most emphasized recommendations for addressing the skills gap are: 1) adding real-world engineering applications into existing courses, and illustrating the real-world impacts through case studies [14, p. 20]; 2) encouraging students' acquisition and synthesis of a broad knowledge base by engaging them in authentic team activities focused on real-world problems via mentors [15]; and 3) structuring multidisciplinary and interdisciplinary student collaborations within universities toward delivering solutions to realistic and authentic scenarios (e.g., [16] and [17]). However, the effectiveness of these processes is not sufficiently explored. Furthermore, transdisciplinarity presents unique curricular and instructional challenges [18], as it requires involving external stakeholders, namely, university-industry collaboration, for achieving higher levels of knowledge compared to multi- or interdisciplinarity [19], [20].

Establishing partnerships with the industry—one of the pillars of transdisciplinary learning—is required to be based on a mutually beneficial collaboration to keep up with growth in new knowledge, rapid technological change, and intense global competition [21]. The time is of essence for the industry as they operate in a fast-changing context making them prioritize "agility" in learning [22]. Therefore, industry partners' commitment to long-term educational programs (e.g, [23]) might soon become infeasible, and sustainable industry collaborations for improving engineering education might depend on ensuring transdisciplinary competence development within shorter periods of time.

Wearable and collaborative robotics as a field presents an additional educational challenge as it is a novel area of robotics and currently requires a collaboration of specific experts from various disciplines around the world. Unfortunately, international collaboration for the education of graduate students is still an understudied area, as mostly research programs are examined (e.g., [24]).

This study fills a significant gap in the literature by examining the effectiveness of the recommended educational innovations for addressing the skills gap. It provides an in-depth examination of graduate students' transdisciplinary learning experiences and outcomes in a short, online course on wearable and collaborative robotics with international partners, to inform further efforts to meet industry demand.

This article is organized as follows. The theoretical framework and details of the online course are provided in Section I. Section II covers the research questions, instructional strategies and tools used, study participants, and data collection and analysis procedures. Section III presents study findings in six areas. Section IV discusses transdisciplinarity as a learning challenge and recommended instructional practices. Conclusions are presented in Section V.

A. Theoretical Framework

Transdisciplinary learning aims to address the world's complex problems based on epistemological pluralism (i.e., discussing and negotiating disciplinary values and knowledge perspectives) with a problem-focused, team-oriented, and integrative learning approach in collaboration with industry and external stakeholders [19]. It differs from multidisciplinary and interdisciplinary learning approaches with its higher levels of disciplinary knowledge synthesis and their real-world applications outside the universities [20]. Creating transdisciplinary competence (i.e., a combination of the required knowledge, skills, and attitudes) involves various subsets of competencies that require not only knowledge, but also intrapersonal and interpersonal skills, as well as certain values, attitudes, and beliefs (e.g., understanding other disciplines and processes of integration, interdisciplinary communication, reflective behavior, valuing transdisciplinary collaboration, and societal and global perspectives) [15]. These automatically bring forth the need for an integrative engineering education approach as in [25]. It is necessary to structure interdisciplinary collaboration among students with different disciplinary backgrounds and facilitate the synthesis of knowledge among different disciplines for transdisciplinary problem solving to help graduates better adapt to the demands of the market and the workplace.

This study views transdisciplinarity as a learning challenge both at the individual and team level. Challenge-based learning [26], [27] was used as the pedagogical framework, in which students were provided with an engaging learning experience that involved investigation and taking relevant actions. Students' learning quality in this process was determined based on three competence domains outlined in [28], namely, the cognitive, intrapersonal, and interpersonal. Students' transdisciplinary knowledge acquisition processes and outcomes (i.e., cognitive domain) were examined by the researchers to determine their transdisciplinary learning quality. Self-regulated learning framework [29], [30] was used to examine students' individual learning processes and determine areas of challenge (i.e., intrapersonal domain). The CATME's teamwork dimensions [31] were used to examine students' teamwork processes (i.e., interpersonal domain).

B. Online Course: "WeCoRD Winter School"

A 5-day online course titled "Components for Wearable and Collaborative Robots" was held by the Open Educational Resources on Enabling Technologies in Wearable and Collaborative Robotics (WeCoRD) Consortium, as part of a 3-year Erasmus+ program (https://wecord.eu). It aimed improving graduate students' transdisciplinary competence through interactive sessions in engineering, industrial design, physiotherapy, and industry quality standards, as well as related skills of self-regulated learning and teamwork. It was offered online during COVID-19 restrictions, and was referred to as the "Winter School."

II. Method

This study used a mixed-methods approach by applying both quantitative and qualitative data collection and analytical procedures, and integrating them during the analysis stage to draw conclusions [32].

A. Research Questions

This study's research questions are as follows.

1) What are the student experiences and outcomes in an intensive online educational program toward improving the transdisciplinary competencies of graduate students in wearable and collaborative robotics? a) What is the nature of transdisciplinary knowledge acquisition? b) What is the nature of self-regulated learning involved? and c) What is the nature of teamwork involved?

2) What lessons can be learned from this innovative approach to improve engineering education toward developing transdisciplinary knowledge and skills of students? a) Which practices are promising? b) Which practices need improving? and c) Which practices need to be added?

B. Student Selection and Placement in Teams

The WeCoRD Winter School program was announced with a flier across various international robotics societies. Applicants were interviewed to check their confidence about communicating in English, engaging in international teamwork, and committing fully to the program. Those who expressed confidence were accepted and 45 students enrolled to the course. They were placed in eight mixed-discipline teams. There were not enough students from design or medical fields to join each team; therefore, each were placed into two teams.

C. Instructional Strategies and Tools

A real problem case from the industry was presented in a video by WeCoRD's industry partner, who was from an international automative manufacturing company, and the teams were assigned the task of providing a conceptual solution to assist factory workers via wearable and collaborative robots. The video included information about the context of the problem, desired outcomes, potential ways to address the problem, and the industry partner's criteria for evaluation. Students were provided with a "5-day design guideline" based on design thinking methodology [33], [34], which suggested that the teams can engage in problem definition on Day 1, generate numerous ideas and select/combine them into one product idea on Day 2, work on industrial design and engineering design of the selected idea on Day 3, continue working on the design on Day 4, and work on their presentation on Day 5. Students were not required to build or test any prototypes.

Slack (Salesforce, Inc., London, U.K.) as a recommended tool for student engagement [35] was used as the main communication medium. The 10-h daily program (8-h in-class and ~2-h out-of-class activities) over five days consisted of 17 interactive online sessions with 19 speakers from Turkey, Europe, the U.S.A., and Russia (see Table I). Students held team meetings, in which they were guided to use MURAL (Tactivos, Inc., San Francisco, CA) for displaying their elaborations. In general Q&A sessions, WeCoRD faculty members mentored students as recommended in [36] to facilitate their transdisciplinary learning. Here, the daily reminders and instructional posts on CATME's effective teamwork were also elaborated on. At the end of the final day, teams presented their solutions to a jury of the consortium members. The program was concluded by the jury's feedback.

TABLE I
DAILY PROGRAM OF THE WINTER SCHOOL

Period	Activities and the tools used
Morning	• Daily instructions on Slack / Warm-ups on Zoom • Instructional speaker sessions on Zoom • Team discussions on Zoom breakoutrooms / Elaborations on MURAL
	Break (45 min)
Afternoon	• Instructional speaker sessions on Zoom • Daily general Q&A and feedback session on Zoom breakoutrooms • Daily reminders / instructional posts on effective learning and teamwork on Slack
	Break (45 min)
Evening	• Team discussions on Zoom breakoutrooms / Elaborations on MURAL • Instructional speaker sessions on Zoom • Team discussions on Zoom breakoutrooms / Elaborations on MURAL • Learning journal entry & team progress report instructions posted on Slack
	Instruction ends
Night	• Journal and report submissions by midnight

D. Study Participants

Two out of the 45 enrolled students dropped out of Winter School early on due to personal reasons. Study participants were 31 (10 female and 21 male) volunteers out of remaining 43 students. They were 22 M.S. and 9 Ph.D. students from 13 different universities in Turkey, Netherlands, Belgium, and Russia studying at the following programs: Mechanical engineering ($n = 13$), biomedical engineering ($n = 7$), physiotherapy ($n = 4$), industrial design ($n = 2$), electrical and electronics engineering ($n = 2$), robotics ($n = 1$), systems and control engineering ($n = 1$), and software engineering ($n = 1$).

The control group consisted of 30 volunteer students (15 female and 15 male), who did not participate in the Winter School. They were 19 M.S. and 11 Ph.D. students from seven different universities studying mechanical engineering ($n = 9$), electrical and electronics engineering ($n = 6$), computer science ($n = 5$), biomedical engineering ($n = 4$), systems and control engineering ($n = 2$), orthotic and prosthetics ($n = 2$), physiotherapy ($n = 1$), and industrial design ($n = 1$).

E. Data Collection and Analyses

Upon Institutional Review Board approval to conduct the study, data collection and analyses were carried out as explained below.

1) Transdisciplinary Competence: A contextual measurement and relevant scoring criteria aligned with the specific learning goals of this Winter School was developed by a team of seven WeCoRD consortium faculty members from engineering, industrial design, and education fields. It was an online form with three open-ended competence questions (see Appendix A) and questions for collecting demographic information. Participants filled out this form both before and after the Winter School. The control group of this study also filled out the form to compare results.

The scoring rubric covered seven areas of knowledge (see Appendix A for sample scoring criteria): 1) engineering design; 2) industrial design; 3) medical; 4) ethics and quality standards; 5) industry perspective; 6) effective learning; and 7) effective teamwork. A 5-point scale was used to rate participants' demonstrated level of knowledge: 5 = Expert (covers at least 5 of the 7 areas), 4 = Advanced (covers at least four areas), 3 = Intermediate (covers at least three areas), 2 = Basic (covers at least two areas); 1 = Limited (covers one area).

Researchers scored responses without knowing to which participant or group (pre-, post-, or control) the responses belonged, and determined the areas and levels of transdisciplinary knowledge demonstrated. Each response was initially scored by two faculty members independently, which yielded 37% overall agreement. Students' short answers were causing disagreements, therefore the scoring approach was revised and students' knowledge of their own field was acknowledged in the scoring. In the second round, scorers went over the responses case by case in pairs, discussed their scoring, and revised their scores independently afterwards. This round yielded 96% overall agreement. Disagreed scores (in four cases) were averaged. Final scores were used to compare the pre-, post-, and control group responses.

2) Online Session Attendance and Participation: Students were expected to fully attend the speakers' online sessions; therefore, participant lists were recorded at random times during the sessions. Using the accumulated lists of attendees, the overall attendance rate was determined. In addition, the results of the polls administered during the sessions, specifically those with the same questions asked both before and after the session, were collected and analyzed to check students' knowledge gain. Such polls were used in 9 out of 17 sessions (53%), in which 12 questions were asked in total. The quantitative knowledge changes in students' responses to these questions were determined and examined.

3) Learning Journal Entries: Students were instructed to submit a journal entry at the end of each day answering questions about the different phases and areas of self-regulated learning (see Appendix B for sample questions). On the final day, they were to write a personal achievement report about what they learned, and their future self-improvement plans.

Journal texts were examined using the grounded theory paradigm [37], [38] and coded using MAXQDA version 12 (VERBI GmbH, Berlin, Germany). The first theoretical categories emerged via open coding (i.e., grouping responses around a particular concept), which showed groups of responses with similar themes. These were further analyzed by axial coding (i.e., putting the data back together in new ways) through asking questions and making comparisons, which yielded a more refined categorization. Finally, through selective coding (i.e., marking specific phrases and expressions linking texts to a core theme) the core categories were determined. This helped researchers identify main themes and create a theoretical model of the nature of effective transdisciplinary learning.

4) Team Progress Reports: Teams were instructed to submit daily progress reports, and a final report at the end of the program. On their first day, they were asked "What are the knowledge, skills, and abilities of the members of your team?" and "What are the expectations for Day 1 and Day 2 in the guide shared today?" to examine their adaptation success and team interaction quality. On days 2–4, they were asked "What information have you gathered as a team today?" "What questions do you have?" and "What is your plan for tomorrow?" to examine their information gathering, questioning, and planning as a team. At the end of day 5, they were to write what they achieved as a team, and an overall evaluation based on the effective teamwork criteria [31] presented to them.

Each team's report was summarized, examined, and discussed by the researchers by creating memos, which were used to make team process conclusions about each team. In addition, researchers argued that better communication facilitated detailed discussions in this setting, which might have yielded more words in reports. Therefore, the average word counts for each team and the median word count for all teams' were calculated to make team interaction quality judgments.

5) Teams' Elaboration Quality: Researchers collected and analyzed teams' final MURAL displays to examine their transdisciplinary elaboration, therefore learning quality. One of the students of the Winter School was included in the analyses to represent the student perspective. Four scoring categories and their criteria were determined by three faculty members and the student representative via examining all MURAL contents.

1) *Engineering Specifics:* a) Definition of the problem (e.g., identification of the need specifications for design such as dimensions, limitations, cost, life, and the input/output of the system); b) design calculations; c) design iteration (e.g., connecting potential system elements via iteration, creating concept design via iteration, comparing alternatives, analysis, and optimization); and d) design evaluation (e.g., construction of the optimized solution via mathematical model/CAD/prototype).
2) *Industrial Design Considerations:* a) Analysis of the user needs and usage environment; b) benchmarking (e.g., researching existing solutions/products); c) creating alternative ideas; d) concept design; and e) detail design (e.g., 3-D modeling).
3) *Medical Considerations:* a) Textual information about the medical perspective; b) visualization of the use case from the medical perspective; c) calculation of the physical benefit for the worker; and d) comparative analyses.
4) *Industry Perspective Considerations:* a) Cost calculation; b) workspace/worker analyses; c) industry standards; and d) Stakeholder identification.

Each teams's MURAL content was rated on a 5-point scale for transdisciplinary elaboration quality: 5 = Outstanding (shows comprehensive consideration covering all four criteria); 4 = Good (shows more than basic consideration covering three criteria); 3 = Satisfactory (shows basic considerations covering two criteria); 2 = Poor (lacking in basic considerations and covers one criterion); 1 = Insufficient (shows no clear evidence of any consideration). The scoring was discussed and iterated by the four scorers to make sure that they reflect each team's transdisciplinary elaboration quality in comparison to one another.

6) Team's Final Presentations: Teams' final presentations were scored by seven jury members, who were three engineers, two industrial designers, one physiotherapist, and one industry executive. This jury used the scoring rubric they developed with four dimensions and relevant criteria.

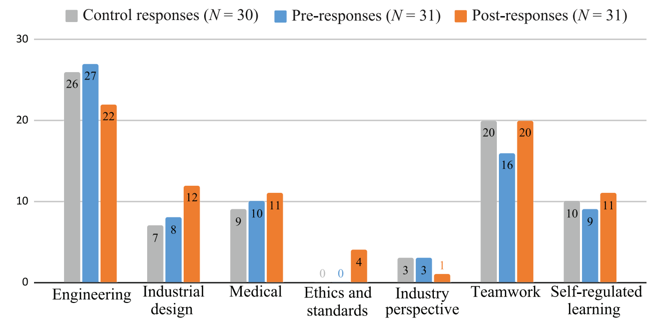

Fig. 1. Areas of knowledge representation in responses.

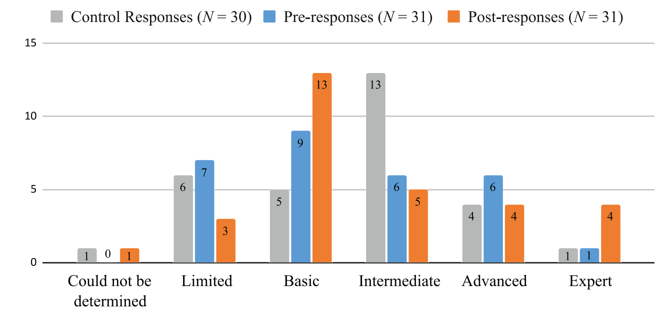

Fig. 2. Levels of knowledge representation in responses.

1) *Engineering design* (seven criteria, e.g., the extent to which difficulties in the implementation, such as manufacturability, are considered).
2) *Industrial design* (12 criteria, e.g., the extent to which the design concept is based on research about people's real needs).
3) *Biomedical/physiological considerations* (12 criteria, e.g., the extent to which the design avoids extra fatigue for the user).
4) *Industry requirements* (five criteria, e.g., the fit between the recommended solution and the problem).

Final presentations were rated on a total of 36 criteria using a 5-point scale (5 = Outstanding, 4 = Good, 3 = Satisfactory, 2 = Needs Improvement, and 1 = Not acceptable). The jury used an online form to rate presentations immediately after each is finished. Presentations were recorded and made available to the jury, for later review, if needed. The scores from jury members in the same discipline were averaged. This resulted in each team receiving an engineering, industrial design, medical, and industry score.

III. Results

A. Transdisciplinary Competence

Transdisciplinary competence score comparisons showed that post-responses ($M = 2.67$ and $SD = 1.32$) were higher than both pre- ($M = 2.45$ and $SD = 1.15$) and control responses ($M = 2.52$ and $SD = 1.15$). Winter School students showed increases in their knowledge of industrial design, medical considerations, ethics and standards, effective teamwork, and self-regulated learning (Fig. 1). Their scores were higher than the control group's in industrial design, medical considerations, ethics and standards, and self-regulated learning. The drops observed in Winter School students' engineering and industry perspective scores were possibly due to fatigue at the end of the program.

Levels of knowledge representation across the three response groups showed that Winter School students' limited knowledge representation was decreased, while basic and expert level representations were increased by the end of the 5-day program (Fig. 2).

The knowledge area and level scores of the three groups of responses were compared using one-way ANOVA to see if the observed differences were statistically significant. The ethics and standards knowledge in the post-responses was found to be significantly higher ($F(2, 87) = 0.01, p < 0.05$). No statistically significant differences were found for knowledge in engineering ($F(2, 87) = 0.19, p > 0.05$), industrial design ($F(2, 87) = 0.38, p > 0.05$), medical understanding ($F(2, 87) = 0.71, p > 0.05$), industry perspective ($F(2, 87) = 0.55, p > 0.05$), teamwork ($F(2, 87) = 0.37, p > 0.05$), or self-regulated learning ($F(2, 87) = 0.87, p > 0.05$). The comparison of the knowledge level scores also showed no statistically significant differences among these three groups of responses ($F(2, 87) = 0.25, p > 0.05$).

B. Online Session Attendance and Participation

Attendance data showed that students did not fully attend the online sessions. Their 4- to 5-day attendance rate was 78%, and each teams' average session attendance was at least four days. Session polling results showed that students had varying rates of correct responses before the sessions (24% to 89%), which increased again at varying rates after the sessions (8% to 50%). Median percent increase in correct responses was 24%. A closer look at each session's data showed that, students' knowledge in employability, and transdisciplinary teamwork was increased by 44% and 43%, respectively. This increase was almost the double of those realized in other sessions, which showed that students were lacking more in these knowledge areas.

C. Self-Regulated Learning Process

Students' daily journals were informative regarding the nature of students' learning, and the areas of challenge they experienced. The main themes that emerged through selective coding are presented in Table II. The nature of learning grounded in the data was approaching this experience with a positive attitude, which was guided by high task value and self-efficacy belief. This attitude was sustained over time, and despite the challenges experienced, the outcome was perceived as a personal success. The basic challenge grounded in the data was synthesizing different ways of thinking and establishing a team dynamic that is supportive and productive. Unproductive teamwork created negative emotions and created an extra burden on students, which affected their effort regulation decisions. The theoretical model that emerged from the main themes is presented in Fig. 3.

Several details stood out in students' journal entry accounts. To start with, their main goal was to increase their engineering, industry, and multidisciplinary teamwork skills to solve

TABLE II
THEMES THAT EMERGED FROM STUDENTS' ANSWERS TO DAILY JOURNAL ENTRIES

Phases	Areas	Main themes
Forethought	Cognition	Specific goals for transdisciplinary knowlegde and skills acquisition
	Motivation	High interest because of links to future goals and since it is a novel/enriching experience High confidence about achieving learning goals, trust in teamwork, and welcoming the challenge
	Behavior	Aiming for active participation Planning to check daily goals and notes, using journal entries to reflect, and checking with others
	Context	Addressing a real problem
Monitoring	Cognition	Partial understanding of the subjects covered from other disciplines General progress towards goals
	Motivation	Supportive teamwork and gaining new knowledge is motivating; unproductive teamwork is demotivating Negative emotions due to struggles with the team dynamics
	Behavior	More effort required when the team does not function well Trying to manage time well by following the resources and structure presented Getting or asking for help from teammates when needed
	Context	Changing with the flow of the program and the team dynamics Both major and minor changes in the tasks engaged
Control	Cognition	Using active learning strategies Learning from other team members Challenged by synthesizing different perspectives
	Motivation	Focusing on self-improvement and the social interaction needed to achieve it Regulating negative emotions by focusing on the work, self-control, and resting
	Behavior	Increasing effort when the team's work does not get finished Persisting despite challenges Getting help from teammates to get things done
	Context	No changes when the task distribution works well; changes when team members do not meet expectations
Reflection	Cognition	Feeling content with the learning strategies used Way of thinking changed with realizations during the teamwork process
	Motivation	High(er) motivation when the team succeeds; low(er) motivation when the team is not supportive or productive Positive emotions when the collaboration works; negative emotions when it fails
	Behavior	Choosing to do what feels comfortable considering the tasks and team dynamics (individual vs. collective work)
	Context	Enriching context, tasks fulfilled Need for more resources to resolve issues during the process
Personal achievement report	Achievement	Feeling successful in transdisciplinary learning and teamwork
	Future plan	Aiming to continue learning from other disciplines and keep improving

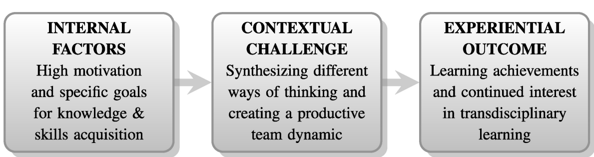

Fig. 3. Theoretical model: Nature of effective transdisciplinary learning.

real-life problems. The two most common reasons stated for the value of this learning were links to their future goals, and seeing it as a novel and enriching experience. On the second day, motivational and emotional challenges appeared in students' accounts, which mostly referred to unfavorable team dynamics as the reasons:

> "Even though I feel like my team isn't motivated, I think I'm paying the required effort. However, I notice that I need to put in more and more effort to keep myself motivated and that becomes harder."

Overall, students' main challenge was synthesizing different ways of thinking, and unfavorable team dynamics made things worse for some students, as it required extra effort to establish a supportive and productive team dynamic:

> "I should really focus on keeping the group together. The engineers, certainly the one who took on the charge from the start, is really focusing down on his mechanical engineering side. He seems not to be listening to other disciplines and tries to put his ideas where he can. He does design nice models in CAD, but this does not give him the right to decide everything within the project."

Some students wrote that they eventually gave up trying. Expressions of disappointment and sarcasm indicated their negative emotional state. Some students expressed "surrendering" or "letting go." Overall, the strategies mentioned for regulating emotions were focusing on work, self-control, and resting:

> "My motivation was actually a little less (today), but I didn't mind. I had to focus on letting go sometimes. During things I didn't have a say, but knew would have good results, I did not intervene or add something."

As the findings from online session participation data showed, students were mostly lacking the knowledge of employability skills, and effective teamwork. In the journal entry accounts, it was seen that problems occurred in teams in these areas, which affected some students' emotional states negatively.

The emotional challenges involved did not seem to have affected students' overall motivation. They mostly reported welcoming the challenge (e.g., "I see this as an interesting challenge and personal development and enrichment opportunity") and intentions to persist (e.g., "I will persevere because

TABLE III
TEAMS' OVERALL INTERACTION QUALITY MEASURED BY PROGRESS REPORT WORD COUNT AVERAGES

Team	Number of members	Knowledge, skills, and abilities of members	Team's learning achievements	Team's overall evaluation	Average word count	Interaction quality (above vs. below the median)
1	6	76	53	59	63	Above
2	7	52	17	83	51	Above
3	5	70	39	48	52	Above
4	5	26	60	45	44	Below
5	6	17	19	62	33	Below
6	4	-	34	92	42	Below
7	4	14	51	57	41	Below
8	5	225	-	96	107	Above
Median of teams' average word counts						48

I have completed more than half of the winter school and victory is just around the corner"). This showed how powerful students' initial goals and motivations were, which helped them adapt to their situations, and express a positive attitude despite the challenges they face.

Students in supportive and productive teams were mostly challenged by the task, and stated that the teamwork and acquiring new knowledge were motivating. This showed how favorable team dynamics can be helpful for transdisciplinary learning:

> "I am still intrinsically motivated to successfully complete this course, and the teamwork with my teammates motivates me even more because I enjoy working together with other passionate engineers and scientists."
>
> "My motivation is improving while I continue to improve my knowledge and to learn applications from different research areas."

Students' overall assessment of this learning experience was that it was enriching, which was another reflection of their positive attitude toward this learning challenge:

> "The tasks that I had to do this winter school affected me to be able to create something from scratch and evaluate it from every perspective. Thanks to the speeches made especially in the sociological and psychological field, I learned to think about the person who will use it while making a design."

D. Teamwork Quality

Daily team reports did not show what information the students gathered to elaborate on, but instead showed the tasks completed, which were generally engineering-driven. Despite reports of discussions, collective decision making, and reaching consensus, the ways students achieved these were not stated. There was no clear evidence to the use of any strategy in their decision-making processes. "Respect" and "appreciation" among team members were reported as the main reasons for "team unity." Teams' overall evaluations provided more details about their teamwork quality. In terms of interaction, 3 out of 8 teams reported to be challenged by: 1) integrating all members' perspectives into one; 2) team members not meeting basic expectations, such as attending the team meetings; and 3) English as the medium of communication. Problems with interaction seemed to have also caused problems with contribution. For instance, Team 6 reported "team members not contributing equally" and "not having a clear road map" to keep the team on track. The quality expectations of the teams were lower in those experiencing challenges with their interactions (i.e., Teams 2, 6, and 7). They reported having pursued "simple" or "satisfactory" outcomes, and that they "did not go above and beyond" in terms of quality. Despite these challenges, teams' reports of their members' related knowledge, skills, and abilities showed that all relevant expertise was found valuable. Five teams out of eight reported having carried out a successful transdisciplinary teamwork.

These findings support the previous link made to the importance of students' teamwork skills. Team progress reports showed that some members' lack of teamwork skills reduced other members' work quality expectations, which resulted in aiming for lesser team outcomes.

A contradiction in the findings was noticed in the case of Team 3. This team was found to be lacking unity by the researchers based on the way they reported their daily progress. However, their overall team evaluation reported their unity as a team achievement. Therefore, report word counts were checked to clarify this issue, which showed certain differences among teams (Table III). It was found that, the teams which reported difficulties with their interactions also had lower word counts in their reports (i.e., Teams 6 and 7) with the exception of Team 2, which had a higher number of members. Team 3's word count was above the median word count, which provided some evidence to their interaction quality. Most of the teams that reported successful transdisciplinary work, also had higher word counts in their reports, as seen in the case of Team 8. This team was also found successful in this sense by the researchers based on the way they reported their daily progress.

E. Transdisciplinary Elaboration Quality

The teams elaboration quality scores varied (Table IV) as some of them provided more detailed evidence of their elaborations with images, drawings, notes, charts, and tables. Teams 1 and 2 showed the highest elaboration quality in their MURAL displays (see Fig. 4 for a sample MURAL, to see all: https://wecord.eu/en/mural). Observed differences among teams helped researchers make evidence-based conclusions about their transdisciplinary learning quality. Medical,

TABLE IV
ELABORATION QUALITY SCORES OF THE TEAMS BASED ON THEIR MURAL CONTENT

Content Categories	Teams' Content Elaboration Scores							
	T1	T2	T3	T4	T5	T6	T7	T8
Engineering Specifics	5	4	3	3	3	4	3	3
Industrial Design Considerations	4	5	2	3	4	3	3	2
Medical Considerations	4	2	2	4	3	2	4	2
Industry Perspective Considerations	4	3	1	3	1	2	2	2
Teams' Mean Elaboration Scores	4.25***	3.50***	2.00*	3.25**	2.75**	2.75**	3.00**	2.25*

*** Good elaboration (4); ** Satisfactory elaboration (3); * Poor elaboration (2).

TABLE V
TEAMS' AREA SPECIFIC AND OVERALL FINAL PRESENTATION SCORES (OUT OF 5)

Knowledge Areas	Teams' Knowledge Area Scores								Overall Knowledge Area Mean Scores
	T1	T2	T3	T4	T5	T6	T7	T8	
Engineering	3.10	3.81	3.67	3.14	3.90	4.19	4.52	3.43	3.72**
Industrial design	3.83	4.22	3.89	3.33	3.76	3.81	4.35	3.78	3.87**
Medical considerations	3.17	3.58	4.00	3.08	4.08	2.50	3.33	2.08	3.23*
Industry perspective	3.00	2.80	3.60	3.60	2.20	2.40	3.40	2.80	2.98*
Teams' Mean Scores	3.27*	3.60**	3.79**	3.29*	3.49**	3.23*	3.90**	3.02*	

** Good representation of knowledge; * Satisfactory representation of knowledge.

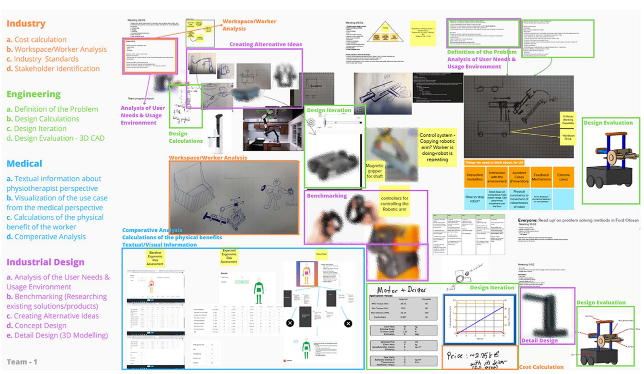

Fig. 4. Team 1's coded MURAL contents.

and industry perspective considerations received lower elaboration quality scores compared to engineering specifics, and industrial design considerations. This finding is in line with the conclusion researchers made from team reports, which was about an overall engineering-driven focus on the tasks.

Team 3 stood out among other teams by receiving the lowest elaboration quality score. Their MURAL content made it clear that they did not put much emphasis on their transdisciplinary learning. This finding shows that despite the program guidance toward transdisciplinary learning, some teams can bypass this challenging route and aim for the final product without paying the required effort for deeper learning. This led to the idea that a case of "groupthink" (i.e., individual members justifying the groups' commitment to a course of action with faulty decision-making processes) [39] occurred in this team. Team 8 received the second-lowest score, which contradicted with the favorable conclusions drawn from their team reports about their transdisciplinary work.

These findings showed that checking teams' elaboration quality via visual evidence can be a reliable and complementary way to make determinations about teams' transdisciplinary learning quality.

F. Final Presentation Performances

Team's final presentation scores showed that students scored higher in the industrial design area (Table V). This adds up with the transdisciplinary competence measure finding showing that students increased their industrial design knowledge the most with this Winter School. Teams received lower presentation scores for medical considerations, and industry perspective, which is in line with the previous finding about teams' lower elaboration quality in these areas. Team 3 was one of the best-performing teams in their presentation despite their lower transdisciplinary elaboration quality. This might be a unique case showing that even when a team does not provide any evidence to their elaborations or learning, they might still present a good idea in the end. Team 8, however, was not such a case. They received the lowest presentation score, which was in agreement with their low elaboration quality score in the previous finding.

IV. DISCUSSION

A. Transdisciplinarity as Learning Challenge

The first research question of this study was aimed at understanding the student experiences and outcomes in an intensive online educational program toward improving transdisciplinary competence. One of the major findings is that transdisciplinary learning was largely affected by the perceived enabling or disabling nature of the team dynamics. Almost all areas of self-regulated learning was found to be influenced by this social factor. Even though teamwork was motivating for the most, some students were emotionally challenged in the process complicating their learning process. These findings are in line with the collaborative learning literature, which states that learners influence one another as knowledge is exchanged and converges through social interaction [40], and that the ability to regulate emotions both individually and collectively determines the effectiveness of collaborative learning [41].

One of the most visible ways the students dealt with the challenges involved while learning in this transdisciplinary context was their positive attitude, which helped them make adaptive behavioral choices when challenged, and persist. This finding is in line with the literature highlighting the importance of certain noncognitive factors for students' success, namely: 1) growth mindset—seeing learning as a flexible and adaptable process; 2) resilience—the ability to accomplish a goal when obstacles make it difficult; and 3) grit—the consistency of interest and passion until a goal is reached [42]. Therefore, students with these qualities can be expected to achieve better in transdisciplinary contexts.

In this Winter School, even though all the criteria for transdisciplinary learning [20] were met, some loopholes were identified, such as some students focusing on the product rather than the process of learning, and avoiding the knowledge synthesis challenge involved. This finding reveals the importance of putting more emphasis on the knowledge synthesis challenge involved in transdisciplinary learning, which is overlooked in the literature (e.g., [43]). Such student tendency must be prevented, as the ability to synthesize knowledge from different disciplines is crucial for creative problem solving and our future [44]. Such prevention seems to depend on addressing the "tensions" expected in collaborative processes [45], and helping students to turn tensions into constructive and productive group processes.

B. Instructional Practices

The second research question of this study was about the lessons learned from this innovative approach to improve engineering education toward developing transdisciplinary competence. Guided daily individual journaling and team reporting was found beneficial to identify the challenges students experienced. Teams' use of MURAL provided evidence to the quality of the team elaborations, therefore their transdisciplinary learning quality. These practices are recommended to be used by other transdisciplinary learning programs.

The most important lesson learned in this study regarding potential improvements was that a clear instructional emphasis on documenting the team processes is critical, particularly of the knowledge synthesis and decision-making processes. Therefore, it is recommended to make "thinking process documentation" mandatory for all transdisciplinary learning programs. The main reason for this recommendation is the fact that no clear evidence was found in this study about how students considered different arguments and made the decisions they made. This reveals the potential risk of groupthink, which is a hazardous way for groups to make decisions both professionally and ethically [39]. It was also seen that students can potentially avoid the learning challenges involved in the process. Therefore, it is argued that a clear documentation of the thinking processes can be used to prevent these issues. This can also help prevent "freeloading" behavior, which creates a negative learning environment and assesment issues for student teams [46].

Regarding ways to achieve this, evidence-based recommendations about effective learning can be used, such as learning via concrete examples, using images to illustrate ideas, and explaining and describing ideas with many details to increase understanding, therefore learning quality [47]. Consequently, using tools like MURAL is once again recommended for students to visually display their team processes. For decision-making, tools to evaluate arguments and multilogical thinking such as [48] are strongly recommended.

C. Limitations of the Study

This study reports findings from an educational case, therefore the findings can only be generalized to the programs with identical goals. One limitation that became apparent was about assessing transdisciplinary competence development. Standard measures would not apply in this case, yet the specific measures developed sometimes did not suffice as well. Not all knowledge areas lended themselves to testing students' knowledge with questions that have correct answers (e.g., ethical design and industry standards). Therefore, students' knowledge gains in these areas could not be determined via instructional sessions. Also, the pre- and post-, open-ended questions used to identify program gains, did not specifically guide students toward which aspects to cover in their thinking. Therefore, the identification of gains was mostly done with the dominant knowledge aspects students demonstrated. One of the limitations of the study that seem to have affected students was the intensity of the program resulting in fatigue. Another such limitation, as the researchers suspected, was a communication issue with the industry partner, which might have led to limited interactions with the students, hence limited learning gains in the "industry perspective" area.

V. Conclusion

This study provides evidence to the benefit of short online programs for transdisciplinary competence development. If such programs can put the required instructional emphasis on students' knowledge synthesis and decision-making processes, contextual challenges can be reduced, and transdisciplinary learning can be achieved more effectively within short periods of time.

Considering the student growth observed in this study, international, week-long online programs are worthwhile to further explore. Joint programs with the industry, based on mutual benefits, such as serving their continuous professional development needs, can facilitate sustained university-industry collaborations to close the skills gap in engineering graduates and meet the market demand.

Appendix A
Open-Ended Questions of the Transdisciplinary Competence Measure, Scoring Areas, and Sample Criteria

1) Please answer this question according to your field.
Engineers: Imagine you need to design a mechanical component for a wearable and collaborative robot. What would you consider in your design? Please explain by giving examples.
Industrial Designers: Imagine you need to work on the design of a wearable and collaborative robot (from concept to realization). How would you plan the design process? Please explain by giving examples.

Health Professionals: Imagine you need or want to use a wearable and collaborative robot for treatment, rehabilitation, or human power augmentation. Explain what you know about what roboticists do to create such a robot. How do they do it, and why? Please explain by giving examples.

2) Imagine you need to learn something new. What steps would you follow? What kind of strategies would you use to learn more effectively?
3) Imagine you became a member of a newly formed team. Your team's task is to solve a problem. What steps would you follow? What kind of strategies would you follow to make your teamwork more effective?

Scoring Areas and Criteria:

1) Engineering design knowledge (problem definition, task specifications, user safety and acceptance requirements, mechanical requirements, functionality, strength, mechanical design safety, manufacturability, etc.).
2) Industrial design knowledge (benchmarking based on relevant industry standards, patents, and existing designs, conducting contextual research with users and on-site observations, evaluating concepts and selecting the best with a team of domain experts, creating prototypes and testing with potential users and getting feedback, etc.).
3) Medical knowledge (considering human physiology in terms of potential difficulties, strains, and other problems that might be inflicted on the human's mind and/or body, and ways to reduce loads and increase the quality of life).
4) Ethics and quality standards (addressing inclusivity and accessibility issues, and current quality standards).
5) Industry perspective (addressing industry needs and applications).
6) Effective learning (goal setting, time and effort management planning, monitoring and controlling emotional/motivational state, applying effective learning strategies, assessing learning outcomes, etc.).
7) Effective teamwork (contributing to the team's work, interacting with teammates by communicating clearly, asking for and showing an interest in teammates' ideas and contributions, keeping the teammates on track by believing that the team can do excellent work, acquiring new knowledge or skills as needed to meet requirements, etc.).

Appendix B
Sample Learning Journal Questions

1) Forethought, planning, and activation-related questions asked on Day 1: a) *Cognition:* What do I know about the topics involved here? b) *Motivation:* Can I deal with this level of difficulty? c) *Behavior:* How will I devote my time and effort? d) *Context:* How do I perceive this task and its context?
2) Monitoring-related questions asked on Day 2: a) *Cognition:* Am I understanding the topics and subjects covered? b) *Motivation:* What is the state of my motivation and what are my emotions? c) *Behavior:* Am I paying the required effort? d) *Context:* Has there been any changes in my context?
3) Control-related questions asked on Day 3: a) *Cognition:* Which learning strategies will I apply for the tasks? b) *Motivation:* Which strategies will I use to improve my motivation and manage my emotions? c) *Behavior:* Will I increase or decrease my effort for the tasks? d) *Context:* Is there a need to change the context or renegotiate the tasks?
4) Reflection-related questions asked on Day 4: a) *Cognition:* Did my learning strategies and ways of thinking work for the tasks? b) *Motivation:* How was my motivation affected and what were my emotional reactions? What were the reasons? c) *Behavior:* What did I choose to do and why? d) *Context:* What is my evaluation of the tasks and their context?
5) Personal achievement questions asked on Day 5: a) What are my achievements and what have I learned? b) How can I improve myself further?

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