Transdisciplinarity for Sustainability in Engineering Education

PhD Dissertation

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To my son Mateu and to all the young people who want “to transform that anger into action” (Greta Thunberg, 23th December 2018)

"If you came to help me, you are wasting your time and mine. If you came because your liberation is linked to mine, then let's join hands and work together"

Ayesha Imam

Institute of the Center for Women's Global Leadership and Women Living Under Muslim Laws

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Abstract

This research aims to improve engineering education in sustainability (EESD) through transdisciplinary learning approaches. The research comprised three phases. The first consisted of the analysis of how sustainability is approached in engineering education through a co-word analysis and characterization of the keywords networks of three relevant journals in the field of EESD over two decades. The journal networks evolution analysis suggested that the concern was growing to move to society. Transdisciplinarity and related keywords constantly dripped along the ten years in all the journals and gained relevance, especially in International Journal of Sustainability in Higher Education (IJSHE) and Journal of Cleaner Production (JCLP). Additionally the IJSHE showed a will of reinforcing relationships beyond the university; the International Journal of Engineering Education (IJEE) gave relevance to real case studies with a North-South component and to students' representativeness; and the JCLP contributed aspects on competences and educational strategies. The characterisation brought as relevant categories towards sustainability those related to cross-boundary schemes (i.e. transdisciplinarity, ethics, networking), institutional aspects, faculty professional development training and learning strategies. Finally, keywords related to transdisciplinarity and collaborative networking spread throughout all the areas of knowledge addressed by the journals, indicating a widening interest.

The second phase studied how emergent EESD initiatives were approached from transdisciplinarity as valued competence for sustainability. The research indicated that most of the initiatives fitted in the problem solving discourse, where co-production of knowledge and method-driven aspects are relevant. Deepening this discourse, most initiatives corresponded to the *real-world argument* promoting science-society collaboration to solve societal problems (EU contexts); others looked for convergence of all sciences (life, human, physical and engineering) in pursuit of human well-being (*innovation argument,* US contexts); and some initiatives brought together students and entities in a team-based learning process with social purpose (*transcendent interdisciplinary research argument*). It is noteworthy that none of the initiatives mirrored the transgression discourse, which attempts to reformulate the establishment, no longer for society but with society.

The last phase consisted in the implementation of a transdisciplinary learning environment experience in the course Action Research Workshop on Science and Technology for Sustainability (5 ETCS) of the UPC Master degree in Sustainability Science and Technology. Civil organisations, public administration, students and educators undertook collaborative research on real-life sustainability case studies, following two cycles of action-reflection. While the course mainly fitted in the *real-world argument* of problem solving, service learning or CampusLab schemes also reproduced a team-based learning with societal purpose (*transcendent interdisciplinary research argument*). We addressed the transgression discourse by means of service learning focusing on social justice, which enhanced the development of complex thinking. Afterwards, some students engaged as professional researchers-activists in the participant organisations. Challenges of their learning process were: problem formulation, process uncertainty, stakeholder's interests and roles integration, and interpersonal skills. Additionally, a well-valued Emotional Intelligence module was developed by the author to help students face some process paralyzing uncertainties.

Finally this work proposes a set of fundamental features to be considered for an effective scheme for a transdisciplinary approach in EESD, methodically framing the science-society discourse on the issue at stake: work in real-world complex problems; involve diverse disciplines and fields cooperation; involve science-society cooperation and mutual learning processes; integrate types of knowledge; rely on disciplinary and cross-disciplinary practices.

Resum

Aquesta investigació té com a objectiu la millora de l'educació en enginyeria en sostenibilitat (EESD) a través d'un enfocament d'aprenentatge transdisciplinar, en tres fases. La primera va consistir en l'anàlisi de com s'aborda la sostenibilitat a EE, mitjançant l'anàlisi de co-ocurrència i la caracterització dels mots clau d'articles de tres revistes rellevants en l'EESD, al llarg de 10 anys. L'anàlisi de l'evolució de les xarxes de revistes va suggerir una preocupació creixent per a traslladar el focus a la societat. La transdisciplinarietat i els mots clau relacionats van degotar constantment al llarg del període a totes les revistes, guanyant rellevància, especialment a la International Journal of Sustainability in Higher Education (IJSHE) i la Journal of Cleaner Production (JCLP) A més, mostrà la rellevància de: la voluntat de reforçar relacions més enllà de la universitat, a la IJSHE; els estudis de casos reals amb component Nord-Sud, i la representativitat dels estudiants, a la International Journal of Engineering Education; i els aspectes sobre competències i estratègies educatives, a la JCLP. La caracterització va aportar com a categories rellevants per la sostenibilitat les relacionades amb esquemes "cross-boundary" (transdisciplinarietat, ètica, treball en xarxa), aspectes institucionals, desenvolupament professional del professorat i estratègies d'aprenentatge. Finalment, els mots clau relacionats amb transdisciplinarietat i xarxes de col·laboració s'identificaren al llarg de totes les àrees de coneixement empreses a les revistes, indicant un interès creixent.

La segona fase va estudiar com les iniciatives de EESD, eren abordades des de la transdisciplinarietat. Indicà que la majoria encaixaven en el discurs de resolució de problemes, que emfatitza la coproducció de coneixement i els aspectes metodològics. Aprofundint aquest discurs, la majoria de les iniciatives s'esqueien a *l'argument del món real* que promou la col·laboració ciència-societat sobre problemes socials (context UE); altres buscaven la convergència de les ciències (vida, salut, física i enginyeria) en la recerca del benestar humà (*argument d'innovació*, context USA); i algunes reunien a estudiants i entitats en un procés grupal d'aprenentatge, amb propòsit social (*argument d'investigació interdisciplinària transcendent*). És rellevant que cap de les iniciatives es va vincular al discurs de transgressió, que persegueix la reformulació de l'"establishment" ja no per a la societat, sinó amb la societat.

L'última fase va consistir en la implementació d'un entorn d'aprenentatge transdisciplinar al curs Taller d'Investigació-Acció (5 ETCS) del Màster UPC en Ciència i Tecnologia de Sostenibilitat. Organitzacions civils i de govern, estudiants i educadors van investigar col·laborativament en casos reals de sostenibilitat, a partir de dos cicles d'acció-reflexió. Si bé el curs encaixa principalment en *l'argument del món real* del discurs de resolució de problemes, els esquemes d'aprenentatge servei o CampusLab poden reproduir *l'argument d'investigació interdisciplinària transcendent* d'aprenentatge basat en equips amb propòsit social. El discurs de la transgressió s'abordà mitjançant l'aprenentatge servei per a la justícia social i va resultar en la implicació professional d'alguns estudiants en les organitzacions civils participants. Els reptes del procés d'aprenentatge foren: formulació de problemes; gestió d'incerteses; integració de diferents interessos i rols; i habilitats interpersonals. Per això, l'autora desenvolupà un valorat mòdul d'Intel·ligència Emocional, animat a fer front a alguns punts paralitzants del procés.

Finalment, aquest treball proposa un conjunt d'elements fonamentals a considerar en un esquema eficaç per a aplicar l'enfocament transdisciplinarietat a l'EESD, que emmarqui de forma metòdica el discurs sobre la qüestió social en joc: treballar sobre problemes complexos del món real; involucrar diverses disciplines i àrees; facilitar la cooperació ciència-societat i els processos d'aprenentatge mutu; integrar tipus de coneixement; recolzar-se en pràctiques disciplinàries i interdisciplinàries.

Resumen

Esta investigación tiene como objetivo la mejora de la educación en ingeniería en sostenibilidad (EESD) a través de un enfoque de aprendizaje transdisciplinar, en tres fases. La primera consistió en el análisis de cómo se aborda la sostenibilidad en la educación en ingeniería, mediante el análisis de co-ocurrencia y la caracterización de las palabras clave de artículos de tres revistas relevantes en el EESD, a lo largo de dos décadas. El análisis de la evolución de las redes de palabras clave sugirió una preocupación creciente para trasladar el foco a la sociedad. La transdisciplinariedad y otras palabras clave relacionadas gotearon constantemente a lo largo del periodo en todas las revistas, ganando relevancia, especialmente en la International Journal of Sustainability in Higher Education (IJSHE) y la Journal of Cleaner Production (JCLP) Además, el análisis mostró la relevancia de: la voluntad de reforzar relaciones más allá de la universidad, en la IJSHE; los estudios de casos reales con componente Norte-Sur, y la representatividad de los estudiantes, en la International Journal of Engineering Education; y los aspectos sobre competencias y estrategias educativas, en la JCLP. La caracterización aportó como categorías relevantes para la sostenibilidad las relacionadas con esquemas "cross-boundary" (transdisciplinariedad, ética, trabajo en red), aspectos institucionales, desarrollo profesional del profesorado y estrategias de aprendizaje. Finalmente, las palabras clave relacionados con transdisciplinariedad y redes de colaboración se identificaron a lo largo de todas las áreas de conocimiento empresas a las revistas, indicando un interés creciente.

La segunda fase estudió como las iniciativas de EESD, eran abordadas desde la transdisciplinariedad. Indicó que la mayoría se correspondían al discurso de resolución de problemas, que enfatiza la coproducción de conocimiento y los aspectos metodológicos. Profundizando este discurso, la mayoría de las iniciativas encajaban con el *argumento del mundo real* que promueve la colaboración ciencia-sociedad sobre problemas sociales (contexto UE); otras buscaban la convergencia de las ciencias (vida, salud, física e ingeniería) en la búsqueda del bienestar humano (*argumento de innovación*, contexto USA); y algunas reunían estudiantes y entidades en un proceso grupal de aprendizaje, con propósito social (*argumento de investigación interdisciplinaria trascendente*). Es relevante que ninguna de las iniciativas se vinculó al discurso de transgresión, que persigue la reformulación del "establishment" ya no para la sociedad, sino con la sociedad.

La última fase consistió en la implementación de un entorno de aprendizaje transdisciplinar el curso Taller de Investigación-Acción (5 ETCS) del Máster UPC en Ciencia y Tecnología de

Sostenibilidad. Organizaciones civiles y de gobierno, estudiantes y educadores investigaron colaborativamente en casos reales de sostenibilidad, a partir de dos ciclos de acción-reflexión. Si bien el curso encaja principalmente en el argumento del mundo real del discurso de resolución de problemas, los esquemas de aprendizaje servicio o CampusLab pueden reproducir el *argumento de investigación interdisciplinaria trascendente* de aprendizaje basado en equipos con propósito social. El discurso de la transgresión se abordó mediante el aprendizaje servicio para la justicia social y resultó en la implicación profesional de algunos estudiantes en las organizaciones civiles participantes. Los retos del proceso de aprendizaje fueron: formulación de problemas; gestión de incertidumbres; integración de diferentes intereses y roles; y habilidades interpersonales. En ese sentido, la autora desarrolló un valorado módulo de Inteligencia Emocional, animado a hacer frente a algunos puntos paralizantes del proceso.

Finalmente, este trabajo propone un conjunto de elementos fundamentales a considerar en un esquema eficaz para aplicar el enfoque transdisciplinariedad al EESD, que enmarque de forma metódica el discurso sobre la cuestión social en juego: trabajar sobre problemas complejos del mundo real ; involucrar diversas disciplinas y áreas; facilitar la cooperación ciencia-sociedad y los procesos de aprendizaje mutuo; integrar tipo de conocimiento; apoyarse en prácticas disciplinarias e interdisciplinarias.

1 Introduction

Actions for sustainability have been promoted from the different areas of environment, society and economy, with the longed for common aspiration to face multiple interconnected sustainability crises in a world that can no longer be conceived as "society without nature and nature without society" (Beck, 1992; Latour, 1993; van Breda, Musango, and Brent 2016). From this imperative for the integration of epistemics from science and real-world, higher education and science become change agents for sustainable transitioning (Stephens et al. 2008). Furthermore, when in last decades the concept of sustainability entered different countries constitutions, turns into framing and regulating human actions (Scholz, 2017).

In this circumstances, society is increasingly requesting universities to be helpful "hybrid partners" in order to cope some kind of challenging problems. New "multiple and sometimes incommensurable missions" (Scott, 2007) and endeavours call for restructuring the university boundaries settings, structures and processes to properly and efficiently use the scientific knowledge to serve society (Scholz, 2017).

Transdisciplinarity emerged in this context with the aim of finding integrated solutions to interconnected problems (van Breda, et al. 2016; Scholz and Steiner 2015a). The purpose relies on integrating expert or academic knowledge with the practical or traditional knowledge from actors outside the academia (Scholz et al., 2006; Brundiers et al., 2010; Brown, 2014) to co-produce outcomes that could be both socially robust and transferable (Steiner and Posch 2006; Scholz and Steiner 2015a) that is, useful for transitioning and scientifically innovative to formulate new guiding principles (Jahn, Bergmann, and Keil, 2012; Lang et al., 2012). The former epistemological structures are step-by-step disrupted and consequently an "epistemic community" gain progressively understanding about new constructed knowledge (Knorr-Cetina 2007; Klein, 2008; Vilsmaier, 2015).

In relation to technological education, the Engineering Education in Sustainable Development (EESD) Conference approved the Barcelona Declaration (2004), declaring that engineers must be able to:

- Understand how their work interacts with society and the environment, locally and globally, in order to identify potential challenges, risks and impacts.
- Understand the contribution of their work in different cultural, social and political contexts and take those differences into account.
- Work in multidisciplinary teams, in order to adapt current technology to the demands imposed by sustainable lifestyles, resource efficiency, pollution prevention and waste management.
- Apply a holistic and systemic approach to solving problems, and have the ability to move beyond the tradition of breaking reality down into disconnected parts.
- Participate actively in the discussion and definition of economic, social and technological policies, to help redirect society towards more sustainable development.

- Apply professional knowledge according to deontological principles and universal values and ethics.
- Listen closely to the demands of citizens and other stakeholders and let them have a say in the development of new technologies and infrastructures.

To achieve these competences, researchers in higher education in sustainability claim for a secondary transdisciplinary structure for organizing work (Jahn, Bergmann, and Keil 2012; Vasbinder et al. 2010; Carew, Wickson, and Radcliffe 2006) which is proposed to be informed by concepts of ‘‘intellectual capital’’ and ‘‘reflexivity’’ (Schneidewind, in Scholz 2015a), more than simply adding new lectures or training exercises in disciplinary courses. Moreover an analysis of the SD competences in the cognitive domain showed that engineering students should have both competences of systemic thinking and transdisciplinarity upon graduating (Byrne et al. 2013; Segalàs, Ferrer-Balas, and Mulder 2010). Therefore a new competences system for sustainability is also needed (Parker 2010; Segalàs and Mulder 2009). This could be achieved on the one hand by providing a deep understanding of the basics; and on the other hand, building capacity for their future professional practice through meaningful learning processes, which are generally not comprehensively integrated in higher education systems (Segalàs et al., 2012).

Eventually, the development and teaching of new sustainable engineering science paradigmatic schemes necessitate new methods and tools (Byrne et al., 2013; Halbe et al., 2015) to create new long-term, participatory, solution-oriented programs as platforms to recognize and engage with the macro-ethical, adaptive and cross-disciplinary challenges. Nevertheless, it is argued that engineering education is far away from this scenario, due to; a) engineering education is usually structured around the search for specific technological solutions; b) the transience terms of most engineering academic projects do not match the long-term relationship and capacity building required for meaningful participatory engagement and transformational change (Benessia et al. 2012).

In the new engineers professional endeavour, the challenges posed by reality are compounded when problem-oriented issues of social, technical and/or policy relevance are involved. Some authors likened the ‘‘border work’’ that is needed in these problem domains to action research (Horlick-Jones and Sime 2004), while some authors consider that experimental action research (Scholz and Steiner 2015a; Scholz 2017; Lewin, 1946) may be seen as a precursor of transdisciplinarity. Indeed, even though referring to the individual, Basarab Nicolescu (1996) holds that transdisciplinarity is simultaneously an attitude and a form of action.

2 Research question

Taking into consideration the needs of engineering education in sustainability and the role that transdisciplinarity learning approaches can play fulfilling these needs, the research question of this work is:

How to improve engineering education in sustainability through transdisciplinary learning approaches?

From this main question the research focused on the next specific questions:

- *What are the patterns and trends of Engineering Education in sustainability?*
- *How has transdiciplinarity been applied in sustainability education, and what is its role in engineering education in sustainability?*
- *Which are the main transdisciplinarity features that enhance engineering education in sustainability?*

To answer the research questions, the present research has been structured in three phases (P1, P2, P3), resulting in three publications (see Table 1). The first phase P1 (see section 3), consisted in sounding out the tendencies in engineering education in sustainability through the analysis of the evolution of research conducted in the field, focusing on the purpose of science in the interface science-society, with a special emphasis on the seepage of transdisciplinarity. Section 3 contains an introduction to the research stage and the first resulting article.

In the second phase P2, the research initially went through the evolution of transdisciplinarity in order to understand its relation with sustainability, conceptualization, and general features, as set out in section 4.1. Then I looked into engineering education initiatives in transdisciplinarity taking place in university courses and clustered them according to the characterization on "discourses on transdisciplinarity" proposed by Julie Thompson Klein (2014). Section 4.2 integrates the introduction to this characterization in the discourses on transdisciplinarity. Both analyses helped us to understand the evolution, trends and different "schools" of the transdisciplinary thinking. Finally, section 4.3 consists in the second article.

The last phase P3 of the research was devoted to the implementation of a transdisciplinary learning environment experience in the course "Action Research Workshop on Science and Technology for Sustainability" of the Master degree in Sustainability Science and Technology, at UPC. Section 5 presents an introduction to the experience and the third publication.

The following Table 1 summarizes the articles published and the journals in the three phases of the research.

Phase	Publication	Journal
P1	Patterns and trends in Engineering Education in Sustainability: a vision from relevant journals in the field (Tejedor, Rosas-Casals, and Segalas 2019)	*International Journal of Sustainability in Higher Education*
P2	Transdisciplinarity in Higher Education for Sustainability: How Discourses Are Approached in Engineering Education (Tejedor, Segalàs, and Rosas-Casals 2018)	*Journal of Cleaner Production*
P3	Action Research Workshop for Transdisciplinary Sustainability Science (Tejedor, Segalas, and Cebrián 2019)	*Sustainability Science*

Table 1- Research phases of the PhD thesis, resulting in three publications in the fields of higher education for sustainability and engineering.

3 Engineering education in sustainability

Looking at preliminary research in scientific journals and at the Engineering Education in Sustainable Development Conference (from 2006 to 2016), two trends were evident: first, from the main focus on purely technical objectives to a problem-solving one in the interface science-society, where transdisciplinar approaches are required to integrate the different knowledge sources (J. Balsiger 2014; Clark and Button 2011); and second to consider appropriate technologies as just another instrument to achieve sustainability, under sustainability's view as a "holistic concept that requires the strengthening of interdisciplinary linkages in the different branches of knowledge" (A/RES/72/223). Moreover, an increased interest in transdisciplinarity has been recognized in science-policy bodies, funding agencies, and public and private spheres, as well as in a ever growing array of disciplinary and professional contexts (Thompson Klein 2014)

Given that engineering principles are aligned with the logic of using scientific knowledge efficiently and properly to serve society (Scholz, 2017), it is claimed to remake the curriculum such that it involves external stakeholders (Knight 2001). In this sense it is argued that engineering education evolve to being engineering problem oriented and further developed into socio-technically oriented (Malmqvist, Kohn Rådberg, and Lundqvist 2015; Hogfeldt et al. 2018). Both academia and professional institutions recognize the need for this curriculum change, despite the tensions between these two institutions' agendas, which are not always aligned (Kolmos et al., 2016).

From this perspective, the aim of the first paper "Patterns and trends in engineering education in sustainability: A vision from relevant journals in the field", was to identify these characteristics taking place in technological universities, through analyzing the evolution of the research conducted in the past two decades1 in relevant publications in the field of engineering education in sustainability.

In order to define the scope of our research, relevant indexed journals were identified through a database search of the terms engineering and education and sustainability in the articles' title and content (years 2001 to 2017), yielding 448 articles (see article, section 2.1). The journals were further filtered for presenting these research keywords in pairs, as follows (selected journal in bold in Table 2):

[1] The last common publication period was used, since the International Journal of Sustainability in Higher Education (IJSHE) is a fully refereed academic journal since 2000.

Research topics (in pairs)	Sustainability & engineering		Sustainability & education	Engineering & education	
Identified journals	JCLP	SUSTDE	IJSHE	JPIEEP	IJEE
Journal Impact Factor	5,6	2,1	1,9	1,3	0,6

Table 2. Data compilation for the journal selection in the Web of Science database based on the paired appearance of the research topics in the Journal Citation Reports categories. Selected journals are shown in bold. The journals are: Journal of Cleaner Production – JCLP; Sustainability – SUSTDE; International Journal of Sustainability in Higher Education – IJSHE; Journal of Professional Issues in Engineering Education and Practice – JPIEEP; International Journal of Engineering Education – IJEE

Two metrics were decisive when choosing between IJEE and JPIEEP, despite IJEE's lower JIF. On the one hand, IJEE had published a greater number of articles fitting the search criteria than JPIEEP. On the other hand, looking at the percentage count of the top ten country contributions to each journal, over 50% of JPIEEP's articles were from the USA (53%). Perceiving a greater contribution diversity to be important, we considered IJEE to be more closely related to our area of expertise and influence, better fitting the scope of our research. The article results are discussed in section 7.2.

3.1 Paper "Patterns and trends in engineering education in sustainability. A vision from relevant journals in the field"

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Patterns and trends in engineering education in sustainability

A vision from relevant journals in the field

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Abstract

Purpose – This paper aims to identify patterns and trends taking place in engineering education in sustainability, through analyzing the evolution of research conducted in relevant publications in the field of engineering education for sustainability in the past decades.

Design/methodology/approach – First, a bibliometric approach has been applied, adopting a co-word analysis based on co-occurrence of the keywords (300 items) in articles from three indexed journals related to engineering, education or sustainability. The selection of the articles has been based on the appearance of the previous three terms in the topic and title fields of the journal, where journal scope (based in the categories of the InCites Journal Citation Reports) covered at least two topics, and the third topic was applied in the search, as follows: *International Journal of Sustainability in Higher Education* – Scope of the journal: sustainability and education, Keyword search: engineering (20 papers); *Journal of Cleaner Production* – Scope of the journal: sustainability and engineering, Keyword search: education (122 papers); *International Journal of Engineering Education* – Scope of the journal: engineering and education, Keyword search: sustainability (29 papers); Second, to identify topological patterns and their evolution, a structural and temporal analysis of the network of keywords and a categorization of the keywords in thematic clusters (named categories) have been performed.

Findings – The most relevant categories in terms of corresponding number of keywords, even though these have decreased in recent years, are those related with institutional and policy aspects to embedding or applying sustainability in higher education. At the same time, categories related to the professional development of faculty members, implementation and use of learning strategies (i.e. real-world learning experiences, educational innovative initiatives/tools/techniques) and cross-boundary schemes (i.e. transdisciplinarity, ethics, networking, etc.) increase their relevance in the past five years, signaling some of the challenging fields of interest in engineering higher education in sustainability in the near future.

Practical implications – Knowledge of the trends in devising sustainability education in engineering allows for designing curricular schemes and learning strategies to achieve competences, which are key factors for the change toward sustainability.

Originality/value – This research has a strong strategic value, as it indicates the focus of future research efforts and networking on some of the topics of greatest concern in engineering higher education for sustainability.

Keyword Complex networks

Paper type Research paper

1. Introduction

Actions for sustainability have been promoted from the different areas of environment, society and economy, with the longed for common aspiration to face multiple interconnected sustainability crises in a world that can no longer be conceived as "society without nature and nature without society" (Beck, 1992; Latour, 1993; van Breda *et al.*, 2016).

In September 2015, countries adopted the sustainable development goals to end poverty, protect the planet and ensure prosperity for all as part of the *2030 Agenda for Sustainable Development: Transforming our world*, with specific targets to be reached. In this context,

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4 Transdisciplinarity in Engineering Education in Sustainability

4.1 Transdisciplinarity conceptualization and its role in sustainability

Since the 1990s, with the introduction of the concept of sustainable development to face complex real world situations, most scholars have agreed that dealing with problems of sustainable development requires a transdisciplinary approach (Komiyama and Takeuchi 2006; Steinfeld and Mino 2009; Lang et al. 2012; Kajikawa 2008; Schneidewind 2010; Jahn, Bergmann, and Keil 2012). In fact, although the notion of sustainability science as a specific body of knowledge and research framework in itself has prevailed, the later has been used synonymously to the idea of 'transdisciplinary research for sustainable development' (Jahn, Bergmann, and Keil 2012) and considered strongly overlaping and interchangeable (Kates at al., 2001). Consistently, Kajikawa defines sustainability science as "a distinct discipline engaged in a transdisciplinary effort arching over existing disciplines" (Kajikawa 2008: 216), which sets the debate back to the need for new ways of producing knowledge to address situations defying disciplinary restrictions. From a transdisciplinary perspective, despite building upon disciplinarity and therefore maintaining its standards, collaboration with society by its very nature adds an additional level of evaluation and quality assurance involving extra-scientific criteria that cannot be found by reverting to established disciplinary standards (Bergmann et al., 2005).

More recently an analysis of the UN's sustainable development goals (SDGs) (especially focused in SDG7, sustainable energy), consider transdisciplinary collaborations as essential in achieving these goals (Fuso Nerini et al., 2018, in: Pereverza, Pasichnyi, and Kordas 2019)

4.1.1 Transdisciplinarity as a negotiation process with an extended peer community

It can be said that science evolves to the extent that it is capable of responding to the main challenges of each era; paradoxically however, while problems posed by sustainability are characterized by unprecedented complexity and uncertainty, continuous technoscientific advances and their practical "solving" applications in ecosystems often become new sources of long term risk. Postnormal science pleads for the management of uncertainty in knowledge and in ethics and for the recognition of different legitimate perspectives and ways of acquiring knowledge (Funtowicz and Ravetz 1993). Thus postnormal science assumes that societal problems are interdependent and not restricted to sectors or disciplines, and breaks free of reductionist assumptions about how systems operate and of the expectation that science delivers the single ''best'' solution or final answer.

Since its inception, sustainability science has evolved to become a problem- and solution-oriented field, inspired by and aligned with post-normal science, that adopts transdisciplinary research practices (Leeuw et al., 2012, Wiek et al. 2012; Lang et al. 2012). This evolution has bifurcated the field into a descriptive–analytical stream and a transformational stream or, in other words, in 'traditional disciplinary-based science for sustainability' and the 'transdisciplinary science of sustainability' (Spangenberg, 2011; Wiek et al. 2012). In short, sustainability science in its transformational mode seeks broad transdisciplinary participation throughout research and practice focused on solving sustainability problems.

Transdisciplinarity, as the active collaboration among various stakeholders throughout society, must be another critical component of sustainability science (Yarime 2012), where shared language is essential to establish bridges of dialogue between science and the world. This requires knowledge and awareness expansion, based not only on an instrumental reason of the means built between specialists, which is fundamental for the resolution of technical problems, but also on a dialogic reason of the ends in which diverse actors participate and engage in dialogue.

Against this background, transdisciplinarity appears as a context-specific negotiation, linked with the concept of Habermas's communicative action[2], which allows social transformation (Després et al. 2004, Thompson Klein 2004). In the negotiation process, not only scientific but instrumental, ethical and aesthetic forms of knowledge are needed and confronted, such that a fifth hybrid type of knowledge progressively emerges: the result of ''making sense together'' or ''intersubjectivity'', which requires an ongoing effort to achieve mutual understanding (Després et al. 2004).

The main role of transdisciplinarity lies in the articulation of both different forms of knowledge and the different levels of reality established by disciplinary knowledge. The "deconstruction" accepts that an object can pertain to different levels of reality, with attendant contradictions, paradoxes, and conflicts (Nicolescu 1996; Max-Neef 2005). This knowledge "articulation" is what brings coherence within the paradoxes and not the "unity" (as the gathering of disciplinary knowledge) (Ramadier 2004), and what allows to reach a systematic and holistic approach while preserving the multi-dimensional aspect of the object of study.

4.1.2 Transdisciplinarity as a way of knowledge production. Transdisciplinarity Mode I and Mode II

When looking at the scientific production of knowledge, Gibbons et al. (1994) put forward a very influential distinction between two models, "Mode 1" and "Mode 2". The authors referred Mode 1 to traditional knowledge production processes, by focusing on hierarchical processes for basic research 'discoveries' within a discipline, featured as the "ivory tower" view of a university. They described it as the 'elderly linear concept of innovation, where quality is controlled by disciplinary

[2] Jürgen Habermas holds three types of rationality (1987): instrumental rationality and strategic rationality based respectively on calculus and effectiveness (which imposes dangerously) and communicative rationality, implying an action to communicate, which allows the social transformations.

peers, and the main interest is derived from delivering comprehensive explanations of the world, though usually not concerned with problem solving for society (Boehm 2015).

Mode 1 has been challenged by Mode 2, “socially distributed knowledge” production, which is organizationally diverse, application-oriented, and transdisciplinary. Problem solving is organized around a particular application, where “tacit knowledge is as valid/relevant as codified knowledge” (Gibbons 1994:3). Quality control is exercised by a non institutional community of practitioners, and success is defined in terms of the usefulness contribution to the overall solution of problems (Boehm 2015). The linear model of innovation has also become challenged by non-linear models of innovation[3], which are interested in drawing more direct connections between knowledge production and the contexts of its application (Carayannis, Campbell, and Rehman 2015). Mode 2, thus, leads to the “engaged university”, where faculty and industry and organisation (public or not) stakeholders network around an application-oriented problem, which illustrates the transdisciplinary process.

Nevertheless, transdisciplinarity was indeed related to Mode 1, in alignment with finding a basis for a unity of knowledge (Scholz and Steiner 2015a; Thompson Klein 2014). From the sociology of science perspective, we may talk about some cultures in the science system which are ‘’non-integratable’’ or ‘’non-relatable’’ (Pickering 1992, in Scholz and Steiner 2015a). Jean Piaget[4] (1972) acknowledged that interdisciplinary relationships work only between neighbouring disciplines with similar structures, methods or validation. To overcome this, he envisioned the development of a kind of meta- (system) knowledge able to operate systems structures in a general way (Scholz and Steiner 2015a). The physicist Basarab Nicolescu aligned with Piaget, but further postulated a spiritual-philosophical belief system as an integrating entity under the perspective of culture (Nicolescu, 2002, 2014). Consequently, Mode 1 transdisciplinarity[5] aspires to develop a meta-structure to perform a more realistic description of material-biophysical and socio-cultural, epistemic structures, which are currently dealt with separately in a myriad of non-neighbouring disciplines in the natural and social sciences, engineering, health sciences, and the humanities, where there is a lack of a cross-disciplinary language and interdisciplinarity seems unfeasible (Scholz and Steiner 2015a; Thompson Klein 2014). The meta-structure will allow consistent relationships between disciplines to overcome paradoxes and reasoning complementarities in theory formulation or modelling.

Mode 2 transdisciplinarity (Gibbons and Nowotny, 1994, Nowotny et. al. 2001) questions the exclusively academic form of research and advocates a social distribution of knowledge through the integration of contextually experiential knowledge (or wisdom) from stakeholders contributing multiple drivers, skills and expertise to reach a more complete understanding of problems. It distinguishes from academia, which shows “no particular inclination to become institutionalized in

[3] “Research can be understood as a form of knowledge production (knowledge creation) and innovation as a form of knowledge application (knowledge use), within a more gen- eral framework and design of knowledge (a knowledge architecture)” (Carayannis 2015:17).

[4] Jean Piaget, epistemologist, biologist and cognitive developmental psychologist.

[5] This notion is called Mode 1 transdisciplinarity as it refers to mere inner science (Gibbons et al. 1994).

the conventional pattern" (Gibbons and Nowotny, 1994: 10), and argues that contextualization of problems requires participation in the agora of public debate. When lay perspective knowledge and alternative knowledge are recognized, a shift occurs from sole ''reliable scientific knowledge'' to the inclusion of a ''socially robust knowledge'' that transgresses the expert/lay dichotomy while fostering new partnerships between academy and society (Nowotny, Scott, & Gibbons, 2001). Against this background, rather than (socio-technological) solutions, orientations are provided for complex societally relevant problems, aiming at the successful development of a given human system.

Both Mode 1 and Mode 2 of knowledge production coexist in research communities, while northern hemisphere academia generally comes from a Mode 1 trajectory and in the southern hemisphere Mode 2 prevails, referring to civic engagement (Watson, 2011: 240-248, in Boehm 2015). Innovation[6] models have been developed from Gibbons et al. (1994) knowledge production models, such as the Etzkowitz's The Triple Helix (2008) that proposed a framework to "managing partnerships interactions among universities, business and government on common projects".

More recently a Mode 3 knowledge production has been introduced (Carayannis, 2012), which is defined as working simultaneously across mode 1 and 2 and emphasizing a knowledge systems perspective in higher education systems. "Mode 3 universities" and systems would be prepared to perform "basic research in the context of application" (Campbell and Carayannis 2013a, p. 34, in Carayannis 2012). Adaptive to current problem contexts, Mode 3 encourages the formation of "creative knowledge environments" and innovative organizational contexts for research and innovation[7]. It does not value individual scholarly contributions so much, but rather emphasises the value of clusters, networks and partnerships (universities, industry, government and civic sector) for "co-opetition", defined as both cooperation and competition (Boehm 2015).

Mode 3, yet unclear regarding the ways of being combined, is proposed to be connected to the Quadruple Helix and Quintuple Helix models of innovation. The Quadruple adds cultural and arts public and civil society as the perspective that specifically brings forth innovation, the "dimension of democracy". The Quintuple Helix translates environmental and ecological issues of concern to possible drivers for future knowledge production and innovation (Carayannis 2012).

4.1.3 Evolution of the conceptualisation of transdisciplinarity

In relation to the evolution of the concept of transdisciplinarity, it is possible to differentiate three periods in time (Thompson Klein 2004), explained below. Table 3 shows the discerning features of these three periods.

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[6] "Research can be understood as a form of knowledge production (knowledge creation), and innovation as a form of knowledge application (knowledge use), within a more general framework and design of knowledge (a knowledge architecture)" (Carayannis, 2012).

[7] Carayanni called it a "Mode 3 Innovation Ecosystem", which allowed "GloCal" (local meaning but global reach) multilevel knowledge and innovation systems.

Time	Conceptualisation Development	Breakthrough	Relevant advocates	Key event	Transdisciplinarity fundamentals
70s	Dialogue between types of knowledge	Associated to interdisciplinarity	Piaget, Jantsch	1st International Seminar on Interdisciplinarity research and education (OCDE 1970[8])	Beyond disciplines Social purpose
80s-90s	Theoretical development	Involvement of external actors	Morin, Freitas, Nicolescu	1st World congress on Transdisciplinarity (Portugal, 1994) Congress on Transdisciplinarity evolution of the university (Locarno 1997)	Knowledge integration Personal commitment
from 2000	Oriented research and processes	Interaction: sociotechnical/ culture/ values	Häberli et al.[9]	International Transdisciplinarity Conference (Zurich 2000)	Real-world problems Science for/ with society[10]

Table 3- Discerning features related to the three periods of evolution of the transdiciplinarity conceptualization (based on Thomson Klein, 2004).

In the first period, from the 1970s to 1980s, a dialogue was established between different understandings and types of knowledge, where the conceptualisation was still highly associated with interdisciplinarity. The discussion on the dysfunctionality of closed disciplinary boundaries and the role of society was prominent at the first international seminar on interdisciplinarity, co-sponsored in 1970 by the Organization for Economic Cooperation and Development (OCDE), in which a fundamental transformation was demanded from universities. Transdisciplinarity emerged there, defined as ‘‘a common system of axioms for a set of disciplines’’ (Apostel et al. 1972) that transcends the narrow scope of disciplinary worldviews through an overarching synthesis. Some participants developed the concept further into two interests. As seen before (see section 4.1), Piaget postulated his inner-science notion of deep interdisciplinary (Mode 1 Transdisciplinary). Instead, Erich Jantsch, an Austrian physicist and system theorist, advocated for the social purpose being the driver for the “coordination of the education/innovation system”, to be called ‘‘transdisciplinarity’’ (Jantsch 1972).

In the next decades, 1980s-1990s, a theoretical development occurred, by means of a broad scientific and cultural dialogue informed by the new complexity view (Thompson Klein 2004). Participants in the first World Congress on Transdisciplinarity (Portugal, 1994) endorsed the

[8] Seminar co-sponsored in 1970 by the Organization of Economic Cooperation and Development (OECD)

[9] Transdisciplinarity: Joint Problem-Solving among Science, Technology and Society. Haffmans Sachbuch Verlarg AG, Zurich, 2000. Workbook I: Dialogue Sessions and Idea Market. ed. R. Häberli et al. UNESCO, Paris, 1998.

[10] J.T. Klein, et al. (Eds). Transdisciplinarity: Joint Problem Solving among Science, Technology, and Society. Birkhauser, Basel, 2001.

Charter of Transdisciplinarity[11] and promoted international platforms and networks, such as CIRET[12]. A fellow CIRET member, Basarab Nicolescu (1996) calls transdisciplinarity "the science and art of discovering bridges between different areas of knowledge and different beings". Another member, the French philosopher and sociologist Edgar Morin, claims for a new dialogue and education reform that bridges humanistic and scientific cultures[13] (Thompson Klein 2004), adding to transdisciplinarity a requirement of personal commitment and openness to different epistemic cultures, experiential contexts, ethics, spirituality.

In this context, the two above explained ideas (section 4.1.2), namely post-normal science and Mode 2 of knowledge production, largely influenced the evolution of transdisciplinarity: the former claiming science engagement in dialogue with everyone who has a stake in a uncertain decision, and the later referring to problem-solving processes transgressing boundaries between science and society.

Regarding the last period and over the last decade of the twentieth century, plenty of oriented research has been developed, enabling the implementation of case study practices and processes. Social, technical and economic development interacted with components of values and culture. In parallel, the need to deal with real-life problems exists, as Mittelstrass stated (1996) "Science becomes transdisciplinarity if it reflects on real life problems" (cited by Scholz at Leuphana Summit, 2012). The International Transdisciplinarity Conference in Zurich in 2000 featured a latest transdisciplinary approach on real-world problem solving, which highlights the convergence of transdisciplinarity, complexity and trans-sectoriality in a unique set of problems that do not emanate from within science. As a conference result, the network td-net[14] was launched by the Swiss Academic Society for Environmental Research and Ecology (SAGUF) and taken over by the Swiss Academy of Sciences (SCNAT) in 2003. Since 2008, the td-net network for transdisciplinary research is a project of the Swiss Academies of Arts and Sciences. Thus, in the Zurich 2000 conference, transdisciplinarity was defined as (Häberli et al. 2001):

> *'Transdisciplinarity is a new form of learning and problem solving involving cooperation among different parts of society. Transdisciplinarity research starts from tangible, real-world problems. Solutions are devised in collaboration with multiple stakeholders. A practice-oriented approach, transdisciplinarity, is not confined to a close circle of scientific experts, professional journals and academic departments where knowledge is produced. Ideally, everyone who has something to say about a particular problem and is willing to participate, can play a role. Through mutual learning, the knowledge of multiple participants is enhanced, including local knowledge, scientific knowledge and the knowledge of industries, businesses, and NGO's. The sum of this knowledge*

[11] The Charter of Transdisciplinarity was signed at First World Congress of Transdisciplinarity, Convento da Arrabida, Portugal, November 2– 6, 1994, Article 14. Available at: nicol.club.fr/ciret/english/charten.htm.

[12] CIRET, Centre International de Recherches et Etudes Transdisciplinaires is a virtual meeting space for specialists from all domains. Publishes an electronic journal; results of UNESCO-sponsored international colloquia (including the first world congress on transdisciplinarity in Portugal in 1994 and the congress on the transdisciplinary evolution of the university in Locarno, Switzerland 1997); and reports on projects around the world http://perso.club-internet.fr/nicol/ciret/

[13] E. Morin, Réforme de pensé congress Quelle universite, transdisciplinarité, reforme de l'universite pour demain? Vers une evolution transdisciplinaire de l'universite Locarno. 30 April–2 May1997. CIRET-UNESCO: Evolution transdisciplinaire de l'universite Bulletin Interactif du CIRET, 9–10 (1997) at http://perso.club-internet.fr/nicol/ciret/.

[14] The Tdnet, Network for Transdisciplinary Research' website (sponsored by Swiss Academies of Arts and Sciences, emanated from International Transdisciplinary Conference, Zurich, 2000), offers an overview of graduate and continuing education in transdisciplinarity projects in Switzerland; complete list of journals and publications; periodical information on transdisciplinarity.

will be greater than the knowledge of any single partner. In the process the bias of each perspective will also be minimized.'

Based on the Zurich 2000 definition, the present work takes the following definition (Lang et al. 2012) of *transdisciplinarity as a reflexive, integrative, cooperative, method-driven scientific principle aiming at:*

a) The solution or transition of societal relevant problems, and concurrently of related scientific problems, by differentiating knowledge from various scientific and societal bodies of knowledge

b) Enabling mutual learning processes among researchers from different disciplines (from academia or other institutions), as well as actors from outside academia, on equal footing

c) Creating and integrating knowledge that is solution-oriented, socially robust[15], and transferable to both scientific and societal practice, including capacity building and legitimization

From the Zurich 2000 inflection point, transdisciplinarity has been stated differently, either focusing on philosophical reflection, critique, or the role of science in society, where some authors argue that interdisciplinary research occurs when there is collaboration between academics, whereas transdisciplinarity involves cooperation with non-academics (Balsiger, 2004; Lang et al., 2012; Scholz et al., 2006; Stauffacher et al., 2006). Thereupon, the common ground between the different currents of transdisciplinarity are their emphasis on the integration of knowledge and the type of reasoning regarding this meta-level, while differring in their specific characteristics of the role of science in society. The US American connotation of transdisciplinary (linked to the public health research context) not necessarily implies engagement with society, but that it "transgresses or transcends" the overlap areas between disciplines, relying still in interdisciplinarity to the degree that it attempts integration of theories, concepts and methods (Stokols 2006; Miller et al. 2008). The European connotation linked to the German and EU context, emphasises that the participation of social actors is pivotal, involving cooperation between researchers and 'practitioners' (Stokols et al. 2008: 79; Pohl et al. 2010).

4.1.4 Mutual learning and knowledge integration in the science-society interface

The engagement of different actors external to academia in research processes is a critical element of sustainability science (Scholz et al., 2006; Brundiers et al., 2010; Brown, 2014), thus these have to be engaged when approaching reality. Contrary to the multi- or disciplinary thinking that addresses fragmented aspects of reality to search for spaces of consensus, and interdisciplinarity that can construct a common model or transfers tools between involved disciplines (e.g. biotechnology, nuclear medicine, etc.), transdisciplinarity goes one step further in the science/society interface (Muhar et al., 2013; Posch & Steiner, 2006; Scholz et al., 2006; Vilsmaier, 2008). The objective is no longer the search for consensus but the search for articulations, preserving the different realities and confronting them in a controlled way. It implies identifying and encouraging bottom-up initiatives for sustainability transitions (Pereverza, Pasichnyi, and

[15] See Gibbons, 1999.

Kordas 2019) of relevant complex societal problems through knowledge integration in mutual learning processes, that is the articulation of transdisciplinary processes (Scholz et al. 2006, Scholz and Steiner 2015a).

Mutual learning between science and society is the key component and ultimate goal of a transdisciplinary process (Pohl, 2008; Russell et al., 2008; Stokols et al., 2008), denoting a process of exchange, joint generation and integration of existing or new knowledge. Transdisciplinarity may be distinguished from other forms of theory-practice collaboration, growing away from the response or reaction of societal actors in consultancy for example, to their conception as partners with equally valuable knowledge (Mobjörk, 2010; Scholz and Steiner 2015a). Jahn et al. (2012) define integration as “the cognitive operation that establishes a novel, hitherto non-existent connection between distinct entities of a given context”. In interdisciplinarity, integration is related to the creation of a common ground, from the critical evaluation of the disciplinary insights, to reach a better understanding. Since transdisciplinarity includes tacit knowledge, bringing different interests, roles and communicative ways, the notion of integration has to be extended. Integration occurs at least at five types of knowledge levels in transdisciplinary processes:

- *Modes of thought*: while the analytic mode (experiencing and understanding) dominates the common work of scientists, the intuitive mode (logical reasoning and cognitive control) prevails on the side of practitioners. The intuitive mode brings a sense of uncertainty with respect to the method but of certainty with respect to the result, and the contrary occurs in the analytical mode.
- *Disciplines*: where disciplines lack cross-disciplinary language, Mode 1 transdisciplinarity aspires to establish consistent relationships between them.
- *Cultures*: human cultures, but also cultures in science, differ with respect to the rules of causation that are accepted, which requires a kind of translation from one to another. Nicolescu’s Mode 1 approach highlights the perspective of culture as a way to integrate seemingly incompatible disciplinary models.
- *Interests*: the challenge of a transdisciplinary process is to mediate between different mental representations as well as values in order to provide socially robust orientations.
- *Systems*: natural, social and economic systems must be integrated in a holistic way to achieve a sustainable transformation.

4.1.5 Problem solving and societal engagement of engineers

It is argued that there is a great divide between ‘science’ and ‘the arts’, which was lamented yet in 1959 by C.P. Snow, and has persisted or probably increased to the present. According to Kuhn's work on paradigm changes in science, this gap was born on the diverse rationalities inherent to the different paradigms (i.e. predict and control in the technological; fascinating in the arts; matching the reality in the scientific, etc.). When a paradigm change comes up, controversy is revealed, given that arguments are not grasped between the new paradigm framework and the establishment (Mulder, 2014; Mulder 2017). Sustainability as a paradigm, poses particular challenges to engineering, which traditionally has applied an ‘expert’ approach based upon a ‘predict and control’ paradigm (Halbe, Adamowski, and Pahl-Wostl, 2015).

Technical and engineering problems differ from other types of scientific problems by a fundamentally different problem solving objective, hence the scientific external applicability and feasibility of the results is in the foreground more than the gain of science-relevant knowledge. Technical and engineering problems include elements from all the different cross-disciplinary ways of approaching problems: the preservation of existing technical development lines (disciplinary approach for purely disciplinary problems); the breadth in major technical projects (multidisciplinary approach for problems that are cross-disciplinary due to their extensive research topic); the merge of issues from distinct technological, technical and scientific fields (interdisciplinary approach for problems that arise from combining different disciplines); or the stimulus to technical innovation through life-world problems, the formulation of which is independent of disciplinary perspectives (transdisciplinary approach for problems rooted outside of science) (Jaeger and Scheringer, 2017).

Regarding engineering education, it is claimed that advancing sustainable engineering science requires creating long-term, participatory, solution-oriented project programs as platforms for the next generation of sustainability scientists and engineers, to enable their recognition of and engagement with the macro-ethical, adaptive, and cross-disciplinary challenges embedded in the cutting-edge problems in their professional field (Seager, Selinger, and Wiek, 2011). Since in 2008, the US National Academy of Engineering (National Academy of Engineering, 2008) listed 14 critical "grand challenges" for societies worldwide, the labeled challenge-based learning has been introduced in many universities and programs (Magnell and Högfeldt 2015). Both challenge-based problem settings (Malmqvist, Kohn Rådberg, and Lundqvist 2015) and transdisciplinary frameworks (Lang et al. 2012; Tejedor, Segalàs, and Rosas-Casals 2018) present similarities with the concept of wicked problems since they are characterized by their focus on "wicked problems", which need creative solutions, their reliance on stakeholder involvement, and engaged, socially responsible science (Bernstein 2015; Ruiz-Mallén et al., n.d.; Owen, Macnaghten, and Stilgoe 2012).

A revealing study of the sociologist and engineer Erin Cech reinforces this view. She points out that a disengagement of engineering students from considerations of public welfare has been detected along their training, which is problematic at both the environmental and humanistic levels, because engineers have to attain the specialized competencies necessary to adequately reflect upon the social aspects (Cech, 2014) and the eco-efficiency (Braungart et al., 2007) of the impact of their work. It is also worth mentioning that it has been traditionally considered appropriate that engineers detach themselves from their work, as the types of problems they deal with are well-structured technological problems (Walther et al., 2012). Nevertheless, it is argued that "a new kind of engineer is needed, who is fully aware of what is going on in society and who has the skills to deal with societal aspects of technologies" (De Graaff et al., 2005). The latter argument leads us to consider the involvement of the community, who might have differing perspectives, aims and paradigms, a key approach to training in higher education (Müller-Christ et al., 2014; Stokols, 2006; Beringer, 2007), particularly of engineering students in sustainability science competences (Segalàs, Ferrer-Balas, and Mulder 2010; Byrne et al. 2013; Tejedor, Segalàs, and Rosas-Casals 2018; Kordas, Pasichnyi, and Nikiforovich 2015). Provided the recognition that, when getting involved with transdisciplinarity, engineering researchers enter unfamiliar grounds for scientific knowledge production (Hirsch Hadorn et al., 2006), new programs evolve, which can be the testing ground for new pedagogies, new teaching incentives, and transdisciplinary collaboration within and beyond academy. In fact, those engineering careers, such as information and communication engineering, design and systems engineering or environmental engineering, further from the traditional core engineering careers, probably better integrate public welfare aspects.

4.1.6 Transdisciplinarity as an approach, not a methodology

Even though the above mentioned 1970 OCDE conference envisioned transdisciplinarity as a set of axioms to be shared by the different disciplines, Gibbons et al. (1994: 5) believed that “transdisciplinary knowledge develops its own distinct theoretical structures”. Transdisciplinarity further adopted a pragmatic approach at the 2000 Zurich conference, which gained popularity, shifting from theory-science deliberations to wondering what it was for in practice (Russell, Wickson, and Carew, 2008; Klein, 2008). This shift emphasized the need for bringing internal reflexivity into any process of transdisciplinary knowledge production, being at the same time a drive, a claim and even "simultaneously an attitude and a form of action" (Klein 2004: 521). This consideration reinforces the idea that transdisciplinarity is an approach, not a theory or methodology (Scholz and Steiner, 2015b; Jahn, Bergmann, and Keil, 2012), even though it can be method-driven, specially within the problem solving scope (Lang et al., 2012; Scholz et al., 2006; Steiner and Posch, 2006).

Regardless of the accuracy in defining transdisciplinarity, some scholars have started to recognize the plurality of understandings of it, arguing that this plurarity depends on specific thematic and socio-cultural contexts (Thompson Klein, 2014; Huutoniemi et al., 2010; Bunders et al., 2010); Hirsch Hadorn et al., 2011). This interest towards exploring plurality is aligned with core values of transdisciplinary ethics and with the transdisciplinary principle of “open encounter” (Pohl et al., 2010).

Other approaches to science–practice collaboration focus on the transformative ability of the application of knowledge for problem solving as action research, transition management (TM), and transformation science (TSc), that attempt to conceive science as a change agent for societal learning and transitioning, and scientists as reflective and reflexive professionals (Wittmayer and Schäpke, 2014). In transdisciplinarity, science functions as a public good and knowledge broker to help develop socially robust orientations, and scientists act as reflexive facilitators. TM proactively supports and mobilizes society actors to take action toward a sustainable future, with scientists also performing the role of activists. TSc takes an active role in increasing societal reflexivity capacity for catalyzing change processes.

4.2 Framing Transdisciplinarity in Engineering Education in sustainability

Taking into account the needs and interests of previous research on engineering education in sustainability and the conceptualization of transdisciplinarity for sustainability, this thesis studied relevant initiatives in engineering education in sustainability with a transdisciplinarity approach. The initiatives identified were clustered according to the characterization proposed by Julie Thompson Klein’s (2014) analysis of one decade of contributions in transdisciplinarity (2004 to 2014). Klein identified three recurrent “discourses on transdisciplinarity”, namely transcendence, problem solving and transgression, which help us understand the evolution, trends and different “schools” of the transdisciplinary thinking.

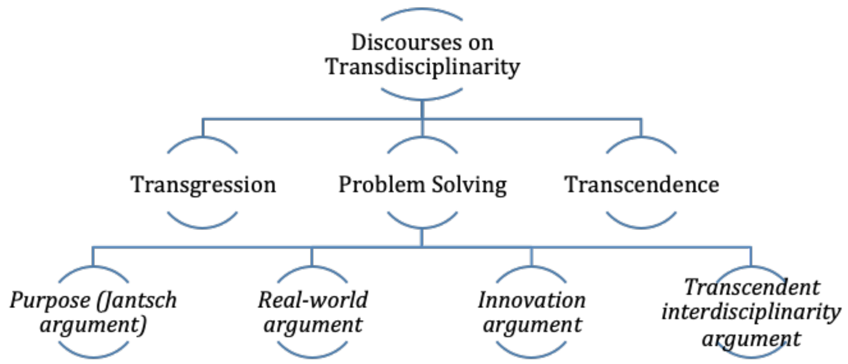

Figure 1- Discourses on transdisciplinarity based on Klein, 2014. The discourse of problem solving presents four additional argumentations.

The main characteristics of these three discourses are outlined below, while a broader explanation is developed in the paper Transdisciplinarity in higher education for sustainability: How discourses are approached in engineering education, in section 4.3.

The first discourse of transcendence retrieves the idea of unity, pursued by different philosophical currents from Ancient Greece to our days, as a search for new syntheses in the contemporary context of growing knowledge fragmentation and the lack of dialogue between disciplines. Addressing this need, transdisciplinarity contributes "articulated conceptual frameworks" that transcend disciplines’ limits of vision. New paradigms, such as post/structuralism, decolonialism, feminism and sustainability, reflected themselves in the new transgressive will framework (Thompson Klein, 2014). Relevant research institutions were constituted in the field, such as CIRET[16], with transdisciplinarity as the starting point.

The discourse of problem solving is not as novel in terms of goals, but is so in methodology. Therefore, transdisciplinarity is understood here as the integration of knowledge and skills of all disciplines to solve or address problems in complex systems or processes in the socio-technical scope. Four different groups are distinguished within, which hold different argumentations in the field of the problem-solving scheme, named “arguments”. The first argument relies on Eric Jantsch’s vision of transdisciplinarity framed by purpose[17], where a model of education is proposed based on the feedback among system design laboratories, function-oriented departments and discipline-oriented departments. Organizations such as ATLAS, the Academy of Transdisciplinary Learning and Advanced Study, follow his vision of the university.

[16] Centre International de Recherches et Etudes Transdisciplinaires. http://nicol.club.fr/ciret

[17] This argument is mentioned in the article as *Jantsch’ education model*

The Swiss-based Network for Transdisciplinary Research, known as td-net[18], brought the real-world argument, which focuses on a investigation with a clearly methodological orientation, where case studies are developed in those areas of human interaction with natural systems and cultural and technical development fields of the life-world. They share with CIRET the vision of complexity, multidimensionality and diversity, but stakeholder's participation is essentially relevant here. This approach is sometimes classified as the Swiss or German school of transdisciplinarity, since it was developed in the contexts of environmental research in those countries, but the approach has been adopted widely in Europe and in the Southern Hemisphere.

The third group encompasses the U.S. National Academies of Science (NAS) roadmap and the Australian-based Integration and Implementation Sciences Network, known as I2S, and focuses on a "convergence of sciences" (life and physical sciences and engineering) for integration and innovation (innovation argument).

The fourth group, led by the American National Cancer Institute (NCI) (2008) and reflected on the emerging field of the Science of Team Science (SciTS)[19], attempts to generate new conceptual and methodological approaches to influence human health and wellness by analysing all affecting factors (social, economic, political, environmental and institutional). Societal participation is also present through the patient's point of view (transcendent interdisciplinary research argument).

The last discourse of transgression is born of a sceptical attitude intending to reformulate the status quo and is related to post-normal science. In fact, transdisciplinarity is seen as a response to the dominant forms of knowledge established by genders, protocols and canons, that marginalize other knowledge attainment alternatives and human rights. The transgressive discourse is also related to social participation and Mode 2 of knowledge, a combination that produces a "socially robust knowledge" that transgresses the academic limits towards society and vice versa.

The methodology of this investigation ranged across a spectrum of quantitative and qualitative approaches. The authors initially developed a review of the literature through a structured search in different databases based on the keywords "transdisciplinary", "sustainability", and "higher education", further refined by "engineer"*(see section 2 of the article). The grouping of the articles allowed identifying those focused on transdisciplinarity approaches in engineering higher education (22 papers). A first qualitative analysis of the whole text corpus of those articles was performed to allocate the different identified initiatives to the discourses on transdisciplinarity. To validate this first qualitative analysis, the authors conducted an affinity analysis to cluster the articles in homogeneous groups, based on the networking tool bibliographic coupling[20].

Finally, a second qualitative analysis was done, where the experiences were classified according to the Balsiger's (2015) taxonomy of varieties of transdisciplinarity frameworks (soft, hard, inclusive

[18] The td-net emanated from the Congress on transdisciplinarity (Zurich, 2000) and is held by the Translab of the Swiss Federal Institute of Technology-ETH, Zurich

[19] National Cancer Institute. Science of Team Science Toolkit. Available from https://www.teamsciencetoolkit.cancer.gov/public/home.aspx?js.1. Accessed 01.07.19.

[20] CSV files were extracted from Scopus articles publications and introduced in VOSviewer 1.6.2 (free computer program for creating, visualizing and exploring maps based on bibliographic or network data http://www.vosviewer.com), which established the links between the different articles based on bibliographic coupling. The bibliographic coupling BCij of two articles i and j is determined by the number of references they share. Then the weighted degree was calculated, which brings the importance of each article in relation with the group and the overall structure of the network (see section 2 of the article).

and reflexive), who came up with ways for moving between limits in a matrix, in terms of stakeholder's collaboration and knowledge integration possibilities, from one variety to another, as well as circumstances change (see article, section 1.2.).

4.3 Paper "Transdisciplinarity in higher education for sustainability: How discourses are approached in engineering education"

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Transdisciplinarity in higher education for sustainability: How discourses are approached in engineering education

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abstract

Sustainability issues, as unwanted results of not fully respecting natural cycles, are widely recognized as wicked problems, which should not be thought of as problems to be solved, but rather as "conditions" to be managed, as if they were a chronic disease (Seager et al., 2011). Thee exists a general agreement on the need to reform scientific expertise by developing new ways of knowledge production and decision-making able to cope with the challenges sustainability poses. In this sense, transdisciplinary aspects of sustainability are acknowledged as a transformational stream of sustainability science.

Transdisciplinarity is considered a competence for sustainability in technological curriculums. Nevertheless, engineering education professionals tread on unfamiliar ground when entering transdisciplinarity approach, as it includes social sciences and humanities perspectives. Advancing sustainable engineering science requires creating new long-term, participatory, solution-oriented programs as platforms to recognize and engage with the macro-ethical, adaptive and cross-disciplinary challenges embedded in professional issues.

Meanwhile, individual university professors and researchers take a step forward to try out innovative experiences in their classrooms to deal with complexity and reach holism in fostering knowledge in different ways. This paper analyses first what is being done and how is it being focused, and second, What are the strategies for and purposes of implementing transdisciplinary experiences in engineering higher education.

Assuming that distinct patterns of definition of transdisciplinary exists, the authors collated transdisciplinary initiatives in engineering education for sustainability from Thompson Klein (2004) *discourses on transdisciplinarity*: transcendence, problem solving and transgression. The also explored how practical constraints imposed by a classroom context, highlighted the limits of transdisciplinarity, and offered suggestions on improvements, which could be implemented. Balsiger (2015) proposes four *varieties of transdisciplinarity* (soft, hard, inclusive and reflexive) to identify ways for moving from one type to another as circumstances change, in terms of stakeholder's collaboration and knowledge integration possibilities.

The methodology consisted in literature review of articles published in relevant journals in the field of sustainability, which focussed on transdisciplinarity approaches in engineering education. We have analysed how the different initiatives fit in Klein's *discourses on transdisciplinarity*. Moreover, an affinity analysis has been performed to cluster transdisciplinarity initiatives in engineering education for sustainability in homogeneous groups. Finally, in the *varieties of transdisciplinarity* framework, the experiences identified when reviewing the literature have been spread over the range among Balsiger's taxonomy.

The investigation indicates that most transdisciplinary initiatives in technological education for sustainability fit in the *problem solving discourse*, where co-production of knowledge and method-driven aspects are relevant. Additionally, they fit in the scheme of broad collaboration and deep integration understood as *hard transdisciplinarity*. Within such discourse, experiences related to "innovation" fit in the *reflexive transdisciplinarity* area, which depends more on the efforts of education entities. It is relevant that none of the experiences analysed seems to fit under the *transgression discourse* paradigm, linked to human rights and emotional intelligence.

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5 Applying transdisciplinarity in engineering education in sustainability: the Action Research Workshop

The next phase consisted in designing, piloting and developing a transdisciplinary learning environment experience in order to enhance sustainability education considering the previous work results.

The learning experience is the 5 ECTS course Action Research Workshop on Science and Technology for Sustainability of the Master degree in Sustainability Science and Technology, at UPC. The purpose of the course is to facilitate the training of students' skills in transdisciplinary work. The course is designed to put together civil society organisations, local administrations, students and educators to collaboratively undertake responsible research, using an action research framework. Participating organisations come from civil society and the UPC itself and collaboration is performed under Service learning and Campus Lab schemes, respectively. The course was analysed during four years.

During the course, students worked on real-life projects related to local sustainability problems, represented by a community entity and constructed with the aim to both respond to organisation requirements and enable students' training and competence achievement (see article, Table 2). A research question agreed on by all the participants served as a guide line for the projects. In each real-life project, students, faculty and stakeholders were asked to complete two cycles of the action-reflection process:

- *Action 1*- Jointly define: project purpose, customer and interest, involved actors;
- *Reflection 1*- Students define: research question, initial situation, needed additional information, action strategy, tasks planning and distribution;
- *Action 2* - feedback from and discussion with stakeholders;
- *Reflection 2* - revise and reformulate.

The course included an Emotional Intelligence Module of 2.5 hours in order to help students to face the uncertainties and complexity of the real-life projects. The implementation of the emotional intelligence module was monitored, yielding a good evaluation by the students.

Additionally, Senior citizens from the Barcelona City Council programme "Aprendre amb la Gent Gran (Learning with the Elderly)" also participated in the course with the intention to add the inter-generational aspect in the learning experience.

An assessment procedure was designed to evaluate both students and the course. Students presented and orally defended two final deliverables: an action research process report, evaluated by faculty and a "client" report (guide, policy paper, communication strategy, etc.) evaluated by stakeholders. A rubric was used by faculty and also by students in a peer assessment. The course was evaluated by direct reflexive questions to students (see article, Table 3)

5.1 Paper "Action research workshop for transdisciplinary sustainability science"

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CASE REPORT

Action research workshop for transdisciplinary sustainability science

G. Tejedor[1] · J. Segalas[1]

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Abstract The Research Institute for Sustainability Science and Technology under the Master degree in Sustainability Science and Technology organises the course action research workshop on Science and Technology for Sustainability (5 ECTS). The authors have been coordinating the course during the academic years 13/14, 14/15 and 15/16. The purpose of the workshop is to put together civil society organisations, local administrations, students and educators to collaboratively undertake responsible research, performing transdisciplinary learning environments and by an action research framework, to answer questions such as: Who are we researching for? Who profits from our research? What are the impacts of our research? Which methodologies and tools should be used when dealing with sociotechnical sustainability challenges? Students work on real projects, related to local sustainability problems, represented by a community entity (Service learning and Campus Lab). Action research methodology is used with a two-cycle approach. In each real-life project, students, faculty and stakeholders are asked to follow the action–reflexion process of action research projects: Action 1—Jointly defining: Project purpose; Customer and interest; Involved actors; Reflexion 1—Students define: research question, initial situation, needed additional information, action Strategy, Tasks planning and distribution: Action 2—Items returning and discussing with stakeholders, Reflexion 2—Revising and reformulating. Having now run the workshop three times, we can conclude that: first, students realised the significance of framing an investigation under a research methodological framework that allows bringing research to the community, enhancing transdisciplinarity in any initiative or action in sustainability science. They set out the importance of some topics and the difficulty to hold them. Second, the formulation of the problem became one of the most arduous tasks in the process; difficulties were mainly related to the perception of the problem from distinct community group motivations. Third, interaction and communication with stakeholders and the recognition of their role was problematic as engineering students are not usually trained to work in wicked problems nor accompany stakeholders during the whole process. Finally, it is relevant to highlight that during the process students faced conflict and frustrating situations both within their team and with stakeholders. To help tackle this problem, an Emotional Intelligence module was introduced in the workshop which proved useful in helping students to solve some paralysing situations, which could otherwise have stopped the progress of the project. We suggest that engineering students need specific training in transdisciplinary research and in conflict resolution, to avoid collapsing in frustration when dealing with real transdisciplinary sustainability transitions.

Keywords Transdisciplinary education · Learning service · Sustainability Science education · Emotional Intelligence education

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CORRECTION

Correction to: Action research workshop for transdisciplinary sustainability science

G. Tejedor[1] · J. Segalas[1] · G. Cebrián[2]

Published online: 11 January 2019

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In the original publication of the article, the co-author Dr. Gisela Cebrián has not been included in the article "Action research workshop for transdisciplinary sustainability science", published in March 2018, Volume 13, Issue 2 of Sustainability Science.

Correct order of author names is provided in the correction article.

The original article can be found online at https://doi.org/10.1007/s11625-017-0452-2.

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6 Global discussion of the three articles results

6.1 Patterns and trends in Engineering Education in Sustainability: a vision from relevant journals in the field

The methodology consisted firstly in applying a bibliometric approach, adopting a co-word analysis based on co-occurrence of keywords (300 items) in articles from three indexed journals related to the terms engineering, education or sustainability, previously identified in a structured way (see article section 2.1). The articles selection (171 papers) was based both on the appearance of two of the previous three terms in the journal scope (based on the categories of the InCites Journal Citation Reports) and on the search of the last term in the topic and title fields of the journal. Further, the network of keywords was structurally and temporally analyzed and the keywords categorized to identify topological patterns and their evolution.

The categorization raised two main blocks in terms of corresponding number of keywords. The more relevant categories[21], though decreasing in the analyzed period, were those related to institutional and policy aspects to embedding or applying sustainability in higher education. The other relevance increasing categories in the last five years analyzed, were those related to the professional development of faculty members, implementation and use of learning strategies (i.e., real-world learning experiences, educational innovative initiatives / tools / techniques) and cross-boundary schemes (i.e., transdisciplinarity, ethics, networking, etc.).

The analysis of the structural network evolution based on the keywords co-ocurrence, highlighted considerations at two levels: the individualised journal networks and the global network.

When looking at the individualised journal network shape, JCLP presented the higher network connectivity, while IJSHE an intermediate level and the IJEE the lower connectivity. A more connected topology (globular shape), with a higher number of long distance connections between nodes, indicates a more global behaviour in the sense that all keywords are much more mutually connected, with the same keywords being used in different articles. A low connectivity (linear shape) suggests that research is made in different areas separately, where articles use different keywords from one another.

When looking at the rest of network metrics and research trends (see sections 4.1 and 4.3, respectively), we had some insight on the networks' evolutionary behaviour. At first (2010), IJSHE showed concern about institutional strategies for sustainability learning and the relation with

[21] Nine categories were identified (see article, section 2.3, Table 3), namely: Institutional and policies; Curricular structure; Educational strategy; Competences/behavioural aspects; Academic/professional development; Sustainability Pillars topics: technoenvironmental; Sustainability Pillars topics: technoeconomics; Sustainability Pillars topics: socio-cultural; Contents referring to social and cultural issues; Transdisciplinarity and collaborative networking

society, even in industrial case studies, reinforcing relationships beyond the university. Along the publication period until 2017, IJEE showed interest in the same areas, namely institutional and curricular aspects of the introduction of sustainability in engineering higher education. In addition, relevance was given to real case studies of education for sustainability in engineering in different countries, with a North-South component. Finally, IJEE presented the highest proportion of articles with keywords related to students' representativeness.

In a first period (before 2013), JCLP predominantly presented topics referring to the adequacy of the institutional and curricular aspects for sustainability. In the second period (after 2013), with a higher number of publications, aspects of educational strategies and competences for sustainability increased. Nevertheless, three areas constantly dropped: transdisciplinarity and collaborative networking, techno-environmental topics and academic professional development and training.

Finally, we analysed the global network modularity, where high modularity represents dense connections between the nodes within modules but sparse connections between nodes in different modules. We used a modularity algorithm (Newman, 2002), which gathered certain keywords in the different proximity grouping, automatically dividing our network into nine different modules or separated domains, where connections between keywords tend to appear more often than in a pure random case. By crossing this automatic atomization in modules (one to nine), with the distribution of keywords in the identified nine thematic Categories, it was shown that only two categories ok keywords were present in all modules, i.e. used in a generalized way throughout the network (see article Figure 5). Specifically, only the keywords belonging to the Categories "Institutional and policies" and "Transdisciplinary and collaborative networking" permeate the entire network, indicating that these topics have spread throughout all the areas of knowledge addressed by all journals.

The results of the co-word analysis and characterization of the keyword networks of the three relevant journals in the field of engineering education in sustainability over the last two decades can be summed up as follows:

- Relevant categories of corresponding number of keywords related to cross-boundary schemes as well as to institutional aspects, faculty training and learning strategies for sustainability
- Regarding the connectivity between different areas in which research was done for each journal, it is suggested that JCLP presents the higher, IJEE the lower, and IJSHE is in between.
- The evolutionary behaviour showed that:
    - Three areas constantly dropped along the studied period, related to transdisciplinarity, techno-environmental topics and academic professional development.
    - IJSHE had a will of reinforcing relationships beyond the university; IJEE gave relevance to real case studies North-South; and JCLP contributed aspects on competences and educational strategies

- Keywords related to transdisciplinary and collaborative networking had spread throughout all the areas of knowledge addressed by all journals.

6.2 Transdisciplinarity in higher education for sustainability: How discourses are approached in engineering education

The second research stage analysed the initiatives in engineering education with a transdisciplinary approach. An initial literature review on the state of the art showed that transdisciplinarity approaches have been introduced, even though not in an extended way, in diverse modalities of learning environments at the technological universities: from compulsory courses in undergraduate programs to external workshops in postgraduate levels. In that sense and also considering results of the first stage, the following considerations emerged:

- Transdisciplinarity can be considered a valuable competence for sustainability in technological curriculums;
- Participatory and solution-oriented programs are suitable platforms to engage with the macro ethical and cross-disciplinary challenges embedded in professional issues;
- The transdisciplinarity approach constitutes an unfamiliar ground for engineering education professionals because it includes societal and humanities perspectives.

After the literature review, the authors matched the identified initiatives to the discourses on transdisciplinarity to generate an overview of how transdisciplinarity was being approached in engineering education. Subsequently, to validate the first qualitative analysis of the authors, an affinity analysis was performed grouping the initiatives in homogeneous groups. The affinity analysis showed experimentally what rationality informs: that authors in a group share similar thoughts. The identification of clusters of articles sharing references enabled to classify them into some of the discourses on transdisciplinarity. Furthermore, the affinity analysis provided a good starting point to identify the discourses on transdisciplinarity, validating the classification proposed.

The research indicated that most of the transdisciplinary initiatives in technological education for sustainability corresponded to the problem solving discourse, where co-production of knowledge and method-driven aspects are relevant. Additionally, they fit in the scheme of broad collaboration and deep integration understood as hard transdisciplinarity.

Scrutinizing the problem solving discourse, the underlying argument that brings transdisciplinarity to the EESD the most is the real-world argument, mainly based on the co-production of knowledge with stakeholders to provide solutions to problems originating in society, with a high method-driven aspect[22]. The innovation argument brings together experiences with an innovational approach that allows stakeholders' perspectives to be present in the design process, intending to achieve the convergence of all sciences (life, human and physical sciences and engineering) for any endeavour related to human well-being. These experiences fit in the reflexive transdisciplinarity area, which depends to a greater extent on the efforts of education entities. The experiences

[22] Most initiatives corresponded to the Transdisciplinary Case Study Approach (TCS) (Steiner and Posch, 2006)

under the transcendent interdisciplinary research argument mainly focused on learning with a social purpose or service learning, bringing together students and entities in a team-based process.

Finally, a few experiences represented the discourse of transcendence. This discourse is related to the Mode 1 transdisciplinarity (see section 4.1.3), which points to the need of a synthetic connotation for the production of knowledge within science. Moving to the individual sphere, this discourse brings the proposal of a kind of professional with a transdisciplinary attitude, who "mediates to the result of making sense together" (Thompson Klein, 2004). The experiences in the discourse of transcendence fitted in the Inclusive transdisciplinarity area.

It is relevant that none of the experiences analysed corresponded to the transgression discourse paradigm, linked to the idea of reformulating the current state of things, where truth can no longer be addressed only by science.

The results of the second research stage can be summed up as follows:

- There is an emergence of learning environments with transdisciplinary approach in technological universities, often led by committed lone professors aiming to engage with the macro ethical and cross-disciplinary sustainability challenges.
- Most of the initiatives fitted in the problem solving discourse and the hard transdisciplinarity scheme. Further examining the problem solving discourse, we realized that:
    - Most of them promoted stakeholders collaboration to provide guidance for problems originating in society (real-world argument, often in EU contexts)
    - Others aimed to achieve the convergence of all sciences (life, human, physical and engineering) in pursuit of human well-being (innovation argument, often in US contexts)
    - Some of them brought together students and entities in a team-based process, focusing on learning with a social purpose (transcendent interdisciplinary research argument).
- None of the experiences analysed fitted under the transgression discourse paradigm, linked to the idea of reformulating the establishment "not for society, by with society".

6.3 Action research workshop for transdisciplinary sustainability science

Aligned with the previous sections regarding transdisciplinarity discourses, the course mainly fitted in the problem solving discourse, such that organisations brought their current complex problem demands to be developed jointly by the multi-stakeholders teams. However, some of the Campus Lab case studies aligned with the transdisciplinarity framed by purpose argument[23] because universities as living labs can provide a potential holistic and iterative framework for the co-production of knowledge from the different university systems (Evans et al., 2015). The real-world

[23] This argument is mentioned in the article as *Jantsch' education model*

argument was present in another big group of real-life case studies, where technological and cultural interactions were at stake, and stakeholder's participation was essentially relevant.

In order to integrate the discourse of transgression, which relies on an attitudinal attempt of criticism and reformulation of reality, service learning was used, focusing on social justice, because it is considered a strategy for action to achieve social transformation through education (Aramburuzabala, 2013). Moreover, the course went a step forward promoting students to take the role of a researcher-activist, going beyond observing and analyzing societal transformations, but rather taking an active role in initiating and catalyzing change processes (Schneidewind et al., 2016). Some of the students continued their final master thesis in the fields, and even some of them engaged as employee-activists at the NGO they were working with.

Students appreciated the Td approaches and mixed research methods, the reflection stages with interesting work and discussion sessions, and the possibility to work in real-life projects with real stakeholders, despite regarding challenging both the integration of different interests and perspectives in the problem approach as well as the recognition of stakeholders' roles during the process. Other challenges of their learning process were: problem formulation, which proved to be one of the most arduous tasks; and the participation of the seniors' learning programme, what however was well valued in terms of intergenerational and personal communication and interpersonal skills. The most successful teams were those able to incorporate to "look at the otherness" and incorporate their expertise (Wiek, Withycombe, and Redman, 2011). Finally, regarding Emotional Intelligence, students highly valued being able to experience some domains of emotional intelligence[24] and the ways emotions can be perceived, expressed or regulated.

7 Conclusions

When sustainability science appeared in the university arena in the early 1990s, academic faculty called for specific frameworks to address the complex problems faced by human society and the natural environment, while retaining relationships with other disciplines. Since then, most professionals have agreed that dealing with problems of sustainability requires a transdisciplinary approach both in research and in sustainability education, and that universities should focus on developing capacity for transdisciplinarity (Jantsch, 1972; Russell, Wickson, and Carew, 2008; Ertas et al., 2003; Jaeger and Scheringer, 2017).

The analyzed EESD initiatives used the transdisciplinarity approach to overcome classical training in technological problem solving, which consists on addressing problems locally only or from one dimension (Scholz et al., 2006) and keeps engineers away from the source of the needs posed to them. This traditional engineering way to address problems mainly focuses on the disciplinary, even multidisciplinary, approaches, closer to "applicability" than to "comprehension". Notwithstanding, problem solving includes elements from all the different cross-disciplinary ways

[24] The module follows the thread of the 5 domains of emotional competence: emotional awareness, emotional regulation, emotional autonomy, social competence, skills for life and well-being, proposed by GROP: Psychopedagogical Counseling Research Group. MIDE, Faculty of Education. University of Barcelona. http://www.ub.edu/ grop/.

of approaching problems, from the purely disciplinary to the transdisciplinary. Moreover, providing socially robust guidance to address life-world problems, the formulation of which being independent of disciplinary perspectives, has to necessarily include the societal context and experience in which they originated.

Regarding the discourses on transdisciplinarity analysis, EESD is appropriate in initiatives related to the discourse of problem solving. The real world argument, consisting on the co-production of knowledge to address societal problems, was mainly based on highly method-driven schemes, as can be action research, considered a precursor of transdisciplinarity. A team-based learning scheme with a societal purpose (transcendent interdisciplinary research argument) can be addressed by means of service learning or team-based CampusLab schemes. We propose addressing the transgression discourse (which remained untackled by the present research) by means of service learning focusing on social justice, which enhances the development of more complex thinking. Afterwards, some students engaged as professional researchers-activists in the participant organisations.

Our research led us to conclude that adopting and developing a transdisciplinary approach in engineering education in sustainability is crucial. The application of a transdisciplinary approach in the Action Research Workshop of the master programme on Science and Technology for Sustainability has been relevant and useful in enhancing the understanding and enabling the learning of sustainability, based on the students' good results, acceptance, satisfaction and commitment, and on the continuity of stakeholders' collaboration. The workshop coordinators' role may fluctuate between facilitators, catalysts and researcher-activists, going beyond observing and analyzing societal transformations, but rather taking on an active role in initiating and catalyzing change processes.

Some lessons learned from the Action research workshop experience were: 1. Engineering students are usually neither trained to work wicked problems nor to work together with stakeholders; 2. Problem formulation was one of the most challenging stages in the AR process, because it meant identifying and characterising the problem by all the participants; 3. Many engineering students lack the collaboration or interpersonal competence, which is crucial for managing collaboration and communication with real stakeholders; 4. The emotional intelligence module proved useful in helping students to solve some situations, which could otherwise have stopped the progress of the project. Regarding their achievements, students understood how incorporating and complementing "the otherness" in a team boosted the knowledge co-creation process, yielding the most successful groups. Students also realized the high significance of taking the research to the community, enhancing transdisciplinarity in initiatives or actions in sustainability science.

Finally this work proposes a set of fundamental features to be considered for an effective scheme for a td approach in EESD, which will allow to methodically framing the science-society discourse about the issue at stake:

- *To work in complex problems originated in real-world contexts*

The complexity of a real-world problem requires moving beyond scientific expertise, even within such an extended peer community setting or an agora of public deliberation.

Any educational engineering experience has to facilitate setting the environment and society in the center, to make them the ultimate goal of technological implementation.

- *To involve cooperation between various disciplines and fields*

Different disciplinary perspectives must be included to reach a common ground.

Transdisciplinary forms of knowledge should complement, not substitute, disciplinary knowledge, connecting what has been disconnected by the ongoing specification and fragmentation of knowledge production in the disciplinary structure. This implies different disciplines jointly working together without leaving their theoretical and methodological disciplinary framework, but adapting common problem formulation and solutions management to the specific situation.

- *To involve cooperation between science and society*

Cooperation between researchers and 'practitioners' has to be established both in the way of approaching problems and in the recognition of non-scientific knowledge as equally valuable, enabling conceptual and methodological shared frameworks.

Some kind of contract or previous agreement should be defined to establish relationship guidelines.

Transdisciplinarity is more than a research approach that is better suited to cope with the complex problems that scientific progress itself continuously creates. Rather, it indeed addresses the relation between science and society. It is interventionist in the sense that it methodically frames, structures, and organizes the societal discourse about the issue at stake.

- *To enable processes of mutual learning between science and society*

The learning experience has to enable processes of exchange, joint generation and integration of existing or new knowledge. The idea behind it is to catalyse achievements by both stakeholders and students, on equal footing, i.e. accepting the otherness, co-leadership and the different interests, epistemics and roles.

For this purpose, co-creation processes may facilitate the matching of contributions, interests and needs. One of the key prerequisites for initiating a successful transdisciplinary process is to negotiate and define a proper goal or guiding question; the process in itself of answering provides benefits to all participating stakeholder groups.

- *To integrate different types of knowledge*

Integration has been largely emphasized as an essential cognitive challenge in the transdiciplinary process. Beyond building bridges between disparate disciplines, the need for communicating in an accessible way comes out. Integration, therefore, refers not only to what we know but to how we communicate.

Knowledge integration and collaborative methods and tools may be experienced as pills or modules in a transdisciplinary-learning environment. The experience of this different way of knowledge creation surely transforms the perception of quality, competence and value of the different sources of knowledge, including lay knowledge.

- *To rely both on disciplinary and cross-disciplinary practices*

Transdisciplinary work is based on disciplinary practice as a rule. Yet, despite being distinct, they are complementary and can enrich each other and eventually reshape internal borders.

Therefore the learning experience should encompass disciplinary practice, as well as multi-interdisciplinary ways to approach technological problem solving. Not everyone has all the required experience, thus the working groups must be formed based on the areas of knowledge and expertise represented and the topics to be addressed.

Finally, we observed some limitations in this research. The experience in the Action Research workshop has been a successful pilot in the context of engineering education for sustainability. Even though the majority of the students were engineers, it was not applied to a regular Engineering Education Degree, but to the Master degree in Sustainability Science and Technology, in which students' high motivation was a key factor. Therefore, it would be necessary to carry out a pilot in a regular degree.

8 Next steps

Once verified how transdisciplinarity can improve engineering education in Sustainability, the most important step is to incorporate this learning approach to "regular" Engineering degrees, which implies university board commitment, curriculum reform, faculty training and process monitoring, with the objective to influence higher engineering education. A continuation of my research might tackle how to bring transdisciplinarity to these undergraduate studies, where new theses can arise from how to involve the institution, how to train teachers, among others. A recent study at UPC (Solé, 2019)[25] shows that an institutional commitment with a clear EESD strategy that encompasses teaching tools and training of faculty is urgent.

In the framework of the Master degree in Sustainability Science and Technology, a new optional subject Social and transdisciplinary research (5 ECTS) started this year, where we address the conceptualization evolution, fundamentals, methods and tools for integration and transdisciplinary approaches for sustainability. However, a single subject may not be enough, and indeed the degree must be organized according to this approach, perhaps around one or more comprehensive projects, where boundaries for transdisciplinary courses are the boundaries of the problem being addressed, not the artificial boundaries of disciplines.

In this sense, a future endeavour will be to apply the transdisciplinary approach to the MCTS in a comprehensive way, involving all the courses and faculty during the master programme reform, which soon is expected to be performed.

[25] L'educació en Sostenibilitat a la UPC. De la Competència en Sostenibilitat i Compromís Social als Objectius del Desenvolupament Sostenible, by the student Nora Solé. Defended on July 2019. Available forthcoming at https://upcommons.upc.edu/handle/2117/123568

9 Publications, conference contributions and participation in research projects related with this thesis

Publications

Tejedor, G., Segalàs, J., Barrón, A., Fernández-Morilla, M., Fuertes, M.T., Ruiz-Morales, J., Gutiérrez, I., García-González, E., Aramburuzabala, P., and Hernández, A. 2019. "Didactic Strategies to Promote Competencies in Sustainability." Sustainability (Switzerland) 11 (7): 1–24. https://doi.org/10.3390/su1102086.

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Conference contributions

Segalas, J.; Sánchez, F.; Horta-Bernús, R.; Busquets, P.; Hernández, A.; Sureda, B.; Lopez, D.; Vidal, E.; Cabre, J.; Martin, C.; Pérez, A.; Tejedor, G. 2018. El proyecto EDINSOST: educación e innovación para la sostenibilidad. Libro de Actas del 6th International congress of Educational Sciences and Development ICESD2018. Setúbal, Portugal, 21-23 de junio de 2018. Pp. 921. ISBN 978-84-09-02091-1

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