PRODUCT Management & Development
An International Journal for Transdisciplinary Research in Innovation

ISSN 2237-5228

Journal homepage
www.pmd.igdp.org.br

Research Article

Characterising the transdisciplinary research approach

Hannah Gooding[1]*, Susan Lattanzio[2], Glenn Parry[1], Linda Newnes[2], Esat Alpay[3]

[1]*Department of Digital Economy, Entrepreneurship and Innovation, Surrey Business School, University of Surrey, Guildford, Surrey, United Kingdom*
[2]*Department of Mechnical Engineering, University of Bath, Bath, Somerset, United Kingdom*
[3]*Department of Chemical and Process Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey, United Kingdom*

Abstract

Despite increasing attention and calls for transdisciplinary (TD) working in engineering, a lack of clarity surrounding what constitutes a TD research approach persists. This paper aims to reduce ambiguity by characterising TD and identifying when the TD approach should or should not be used. Specifically, the research answers the question: when might it be beneficial to take a TD rather than a single, multi or interdisciplinary research approach? Survey responses from twenty-eight authors (50%) who presented papers at the 28th ISTE International Conference on Transdisciplinary Engineering (TE2021) were qualitatively analysed. Findings show a TD approach to research is beneficial for complex problem-solving. New understanding reveals that TD could be used to evidence scientific and social impact, and that context determines the appropriateness of TD adoption. However, even where TD adoption is deemed appropriate, institutional barriers to adoption may exist. In other words, the work environment (culture) in which we do our research, may determine if any meaningful benefits from TD are, or are not realised. Lessons from engineering education are used to discuss how to institutionalise TD, future transdisciplinary engineers and researchers might be taught and socialised in the competencies needed for transdisciplinary research.

Keywords: transdisciplinarity, transdisciplinary, transdisciplinary engineering.

1. Introduction

Society is facing complex challenges, from the impact of changing weather patterns on food production to migration to renewable energy sources and global health management (Scholz, 2020; United Nations, 2022; Gollakota and Shu, 2022). These problems are interconnected and span multiple boundaries, to seek effective solutions researchers must consolidate different organisational and academic disciplines (Hirsch et al., 2008; Hyun, 2012). Within the literature there are different types of disciplinary working (Wognum et al., 2018), to achieve collaboration the adoption of a transdisciplinary (TD) approach to research, where people from different disciplines openly exchange ideas, is required (Hyun, 2012).

Within engineering, collaboration between disciplines supports long-standing commitments being made by industry towards sustainable development (UK Research Innovation Council, 2020; European Commission, 2021; Broo et al., 2022). In "Industry 4.0" TD research approaches were utilised to address socio-technical concerns (Hyun, 2012). Currently in "Industry 5.0" cyber and physical systems are intertwining, meaning that future products are designed and developed in seemingly transdisciplinary environments (Broo et al., 2022). As such, the distinction between traditional disciplines, such as mechanical, electrical and computer engineering, is narrowing (Broo et al., 2022). Nonetheless, terms of inter-, multi- and transdisciplinarity are often used interchangeably (Lattuca & Knight, 2010), potentially compromising the effectiveness of an *actual* TD approach.

Despite interest in TD ways of working, TD research approaches continue to be understudied and within the literature, the meaning of inter-, multi-, and transdisciplinarity lack clarity. Disagreement exists regarding which specific characteristics of transdisciplinarity distinguish it from the other disciplinary approaches (Pohl, 2011; Wognum et al., 2018). Theoretically, a lack of consistency regarding exactly what constitutes a TD approach to research means the impact of TD in comparison to "competing" approaches cannot be assessed (Wognum et al., 2018). In practice, it is challenging to introduce TD research in engineering. A mismatch occurs between the uncertainty regarding terms that underpin the TD research approach and the principles of accuracy and precision underpinning engineering specialisms (Menoni, 2006; Kollman & Ertas, 2010; Leach & Rogers, 2010).

Received: November 23, 2022. Accepted: December 12, 2022.
***Corresponding author:** HG00202@surrey.ac.uk

To understand what distinguishes TD from other disciplines a coherence in knowledge is needed (Ramadier, 2004; Faulconbridge, 2010). Only then can we determine when and where TD is used, as well as its impact in comparison to the other disciplinary approaches (Lattuca & Knight, 2010; Faulconbridge, 2010; Taajamaa et al., 2013; Wognum et al., 2019). This paper aims to provide coherence by identifying the predominant characteristics of TD. To achieve this aim, the literature on TD definition and characterisation is first examined to gain clarity of meaning. Then, utilizing a survey, expert opinion was captured by asking: when might it be beneficial to take a TD rather than a single, multi or interdisciplinary research approach?

This paper is structured as follows: the literature associated with TD is investigated, including TD within the engineering context (Section 2); the data collection and analysis methods are described (Section 3); findings are presented and evaluated in the light of the existing literature (Section 4); lessons from engineering education are applied to discuss how TD can be institutionalised by developing a tradition and culture in higher education (Section 5); conclusions are formulated and future work proposed (Sections 6 and 7 respectively).

2. Literature

The term "transdisciplinary" was coined at an Organisation for Economic Co-Operation and Development (OECD) conference in France on interdisciplinary teaching and research (Klein, 2003; Taajamaa et al., 2013; Tejedor et al., 2018). A paper by the author, Jean Piaget, which initially conceptualised interdisciplinary and transdisciplinary was presented at the OECD conference, giving the theoretical groundwork for Jantsch, who after receiving the paper built upon Jean Piaget's work. The definition of TD provided by Dr Erich Jantsch's work: "The coordination of all disciplines and interdisciplinary in the education/innovation system based on a generalized axiomatics (introduced from the purposive level) and an emerging epistemological pattern" (Jantsch, 1972), underpins the theoretical development of this paper. Although inspired by Jean Piaget's work, Jantsch is critical of the stratified system which Piaget (1972, p. 17) describes, whereby science is elevated without purpose; instead, Jantsch holds quite the opposite belief: proposing that systems are dependent upon the purpose attached to it, which comes from individuals' values. Jantsch goes on to criticize Piaget's understanding of science as a rigid property, by asserting that such views are too mechanistic. Jantsch, on the other hand, accepts science in its constrained positivistic sense by acknowledging the advantages of rigidity found in lesser levels of coordination. Jantsch (1972, p. 19) thought that the scientific realist approach produces a conflict with relativist perspectives in social systems at higher levels of coordination when various disciplines collaborate. In opposition to Piaget, Jantsch notes that universities often try to orientate towards rigid models of society and that such a static view is "out of tune" with the world and cultural patterns of today (Jantsch, 1972, p. 9, 10). Jantsch proposes embracing the evolution of the non-linear. Societies, cultures and institutions should not be forced into linear systems in which they do not fit. Instead, Jantsch tries to get rid of this linear mechanistic view of 'levels' and speaks of innovating education: changing the system itself to accommodate non-linear reality.

Jantsch identifies two barriers to inter- and trans-disciplinarity. The first is the rigidity of disciplines, where disciplinary concepts and axioms from the lower levels anchor individuals in current knowledge, preventing them from learning from others, and the second is the application of these axioms (a statement that is taken to be true) to higher levels. He suggests that while attempting to work at "higher" integrative inter- and trans-disciplinary approaches, holding mono-, multi-, plural-, and cross-disciplinary notions as true, might result in barriers. He proposes the system parties focus on a shared purpose and agreed on axioms so that the system can move toward a state of coordination, despite the parties holding different ontologies and epistemologies. Coordination for Jantsch was the development of education integrating the scientific-technical and psychosocial sides of the education/innovation system.

The TD approach is complex and dynamically changing, requiring continuous self-renewal of human capabilities (Jantsch, 1972). Therefore, Jantsch proposes that TD should emerge from the purposive level. One must learn to know, do and be simultaneously; thus, creating a space in which open unity and complex plurality exist mutually (McGregor, 2004). To expand on McGregor (2004), essentially to achieve a TD state, openness to all realities as they appear is essential. Moving into new intellectual spaces requires us to understand fundamental differences in ontologies and epistemologies; whilst at the same time comprehending that this understanding does not have to lead to, or be coupled with, conflict or tension (McGregor, 2004).

After Jantsch's and Piaget's papers, little progress was made in TD theory and the term was not heavily cited until the 1990s when the use of transdisciplinarity to address complexity arose during climate change conversations (Bernstein, 2015; Repko, 2009). At this time two TD discourses emerged: the Nicolescuain and the Zurich schools of thought (Pasquier & Nicolescu, 2019).

The Nicolescuain School conceptualised TD through complexity science (Lattanzio et al., 2021). To demonstrate the connections between quantum physics and the school's aim for a "unity of knowledge" (McGregor, 2015), the example of light can be used. Light exists in dual realities, behaving as a particle and a wave or both. Similarity is found in the appearance of TD in the concept of uni-duality. In mono-disciplinary approaches, we learn about individual elements, which are appropriate to specific problems, but we know less about the whole (Ertas et al., 2003; Leach & Rogers, 2010; Wognum et al., 2019). Inter- or multi- may capture interactions between parts, but miss the global view, the uni-multiplex which tells us of the system (Anselmo, 2018). TD is the ability to understand the language and culture of other disciplines. This is more than communication; it is a unity of knowledge as we need to know both the overlapping and the non-overlapping aspects of each disciplinary approach; what is essential is not just the unity of knowledge but the coherence of it (Ramadier, 2004).

The Zurich school arose from a conference in March 2000 (McGregor, 2015). Encompassing notions of practicality, the Zurich School conceptualizes TD research and knowledge generation as developed from and focused on real-world problems (Hollaender et al., 2008; McGregor, 2015; SCnat Knowledge, 2022). The Zurich school promoted the work of Gibbons et al. (1994), who discerned a distinction between fundamental research motivated by the development of scientific knowledge within disciplines (Mode 1) and research motivated by real-world problems (Mode 2) (Gibbons et al., 1994). TD may be characterized as Mode 2, as research is carried out within the applications context, knowledge is generated because of problem-solving (Lattanzio et al., 2020).

In the early 2000s, TD approaches to research were recommended to enable the management of rapid developments in technology occurring at the time, work on introducing TD models began by Ertas in engineering education (Ertas et al., 2000, 2003). Transdisciplinary engineering (TE) focuses on fusing science and management concepts to create a unified transdisciplinarity entity for engineering design (Ertas et al., 2000). To enable the engineering workforce to perform increasingly complex tasks of synthesis, engineers' cognitive and perceptual capabilities should facilitate the development of T-Shaped skills (Noor, 2012), i.e. skills which encompass depth and breadth of subject matter simultaneously. Expectations from accreditation boards for Engineering and Technology honour this shift, demanding graduates who are better trained in interpersonal skills such as globalization, communication, and leadership (Plumblee et al., 2012; Royal Academy of Engineering, 2022).

2.1. Characterising transdisciplinarity

The terms inter-, multi-, and TD are employed by many authors, but perceptions and understanding of what constitutes approaches may differ (Pohl, 2011; Renn, 2021). To address the challenge, Carew & Wickson (2010), identified characteristics of TD from research in the literature (Table 1). The authors compartmentalize TD as a construct, breaking it down characteristically. In this paper, we draw on Ertas (2010), whose language aligns with engineering, and Pohl (2011) who proposed four main features of TD research in his "approachology" (Table 1).

Table 1. Characteristics of transdisciplinarity.

Characteristic	Carew & Wickson (2010)	Ertas (2010)	Pohl (2011)
Involvement of Various Stakeholders		Eliminates disciplinary boundaries for strong collaboration	Participatory research
Transcendence and Integration	Transcending and integrating	Redefines boundaries by bridging between natural science, social science, humanities, and engineering	Transcending and integrating disciplinary paradigms
Problem Solving Capability	Practical problems, problem orientation	Use of shared concepts, frameworks, tools, methodologies, and technologies to solve common unstructured research problems	Relating to socially relevant issues
Unity of Knowledge	Evolving methodology	Shared common conceptual frameworks, tools, methodologies and tools leads to the development of new knowledge	Searching for a unity of knowledge

We further explain the characteristics in Table 1:

1. **Involvement of Various Stakeholders:** "Various stakeholders" refers to the inclusion of stakeholders from different academic disciplines, social sectors and non-academic professions (both private and public) for the reorganization of knowledge towards socially relevant issues (Pohl, 2011; Klein, 2003).
2. **Transcendence and Integration:** Transcendence in TD occurs when dynamic frameworks enable collaboration between hybrid actors (Carew & Wickson, 2010). Collaboration is evident in multidisciplinary and interdisciplinary research but does not reflect the search for mutual understanding amongst stakeholders inherent in TD approaches (Faulconbridge, 2010; Rasmussen et al., 2010; Schikowitz, 2021). Integration in TD occurs when researchers conduct research that crosses and integrates disciplinary paradigms to solve societal challenges rather than just academic ones (Pohl, 2011).
3. **Problem-Solving Capability:** The ability to solve complex societal problems is an accepted characteristic of TD (Carew & Wickson, 2010; Tejedor et al., 2018). Of the disciplinarities, only TD is proposed as suitable for dealing with society's complex and multidimensional challenges (Kollman & Ertas, 2010; Wickson et al., 2006; Tejedor et al., 2018). Neither mono-, inter- or multi-approaches foster the collaboration and synthesis required to generate boundary-crossing solutions to complex large-scale challenges (Ertas, 2018). The increasing importance of investment into ethical artificial intelligence (AI) exemplars such characteristics. Where practical problem-solving enables transdisciplinary collaboration to bridge the gap between idealised principles of AI morals as they appear in published papers to the existence of principles in reality (Borg, 2021).
4. **Unity of Knowledge:** similar to transcendence, knowledge unity aims to produce societally useful knowledge (Pohl, 2011). The distinction discerned here is that whilst transcendence focuses on producing societally relevant knowledge through people-centricity (ie integration, collaboration, individuals, and teams). Unity of knowledge focuses on the reorganisation of academic knowledge to make it useful for addressing socially relevant issues (Pohl, 2011). Understanding "what" and "why" characterises the unity of knowledge. TD generates knowledge across disciplines (Pohl, 2011) and inherently there cannot be a single research technique (Augsburg, 2014). Actors share understanding through knowledge frameworks that exist in boundary-less systems where disciplinary barriers are removed (Piaget, 1972), allowing techniques to be tailored to the environment and challenges (Wickson et al., 2006).

More recently, work in sustainable development and policy, has created further understanding as to what comprises a TD research approach by generating new characteristics see: (de Jong et al., 2016; Lawrence et al., 2022). Authors publishing between 2019-2022 provide double the number of characteristics that were originally presented by Wickson and Carew in 2007. Although this develops the context of TD, it provides problems for cohesiveness. Perhaps TD's true meaning is being elaborated with time (Nicolescu, 2002). This is evidenced when reviewing the most recent UK Governments scientific toolkit (Government Office for Science, 2017) and UK Research Innovation and Development roadmap (HM GOV, 2020). Although the general policy environment does not explicitly use the word TD, interdisciplinary is frequently used to describe approaches that are more of a TD nature.

Having summarised the characteristics of TD, we utilise these to analyse expert answers to our research question: when might it be beneficial to take a TD rather than a single, multi or interdisciplinary research approach?

3. Method

Research began with a literature review that identified ambiguity in terminology and characteristics employed to define TD. The work of Carew & Wickson (2010), Ertas (2010) and Pohl (2011) was identified as providing clear definitions of TD characteristics. These characteristics were used to construct a theoretically grounded analytical framework, which was used to analyse textual data. Data came from a survey of twenty-eight authors presenting papers at The 28th ISTE International Conference on Transdisciplinary Engineering (TE2021). The survey captured expert opinion from those with expertise in TD engineering by asking: "When might it be beneficial to take a TD rather than a single, multi or interdisciplinary research approach?". Responses were received via email. To preserve anonymity and help remove bias responses were copied and personal details removed, with each response given a sequential number. To identify when TD as a research approach should or should not be used, text responses were analysed using the thematic qualitative analysis of Braun & Clarke (2006) undertaken in six steps (Table 2).

Table 2. Phases of thematic analysis adapted from (Braun & Clarke, 2006).

	Stages	Description
1	Familiarising yourself with the data	Reading and rereading the data and noting down initial ideas
2	Generating initial codes	Coding interesting features in a systematic fashion across the entire dataset; collating the data relevant to each code
3	Searching for themes	Collating codes into potential themes; gathering all data relevant to each potential theme.
4	Reviewing themes	Checking if the themes work in relation to the coded extracts and the entire dataset.
5	Defining and naming themes	Ongoing analysis to refine the specifics of each theme, and the overall story the analysis tells, generating clear definitions and names for each theme.
6	Producing the report	The final opportunity for analysis. Select vivid, compelling extract examples, final analysis of selected extracts, relating analysis back to research question and literature, produce a scholarly report of the analysis.

To begin with, a single researcher (the corresponding author) conducted a deductive analysis. With the research question in mind, literature was examined, and all quotes were coded thematically against the characteristics of TD (Table 1). Then, an inductive procedure was conducted to avoid logical fallacy: i.e., to not force an answer out of the data. With no reference to literature, the researcher re-examined the data and clustered it according to how themes existed in the data set alone. Conducting both inductive and deductive procedures creates an adductive approach, allowing comparison of both categorisation's results, thus confirming the validity of findings. New areas, not highlighted by the deductive approach, arose during the inductive enquiry. In this analysis, the dominant thesis of each respondent is reported in form of characteristics to place focus on differences and similarities in individuals' core understanding of the application of TD.

4. Results and discussion

Results from the analysis of expert comments nearly all matched characteristics from the literature (Table 1). One respondent (#22) is an exception (see Table 3), as the response cannot be neatly classified into either 1-4 characteristics. Respondent (#22) is not excluded from the study, rather their response is expanded on, in full, in section 4.5 of the paper. In addition, although respondents (#12) and (#23) comments are included in the Problem-Solving Capability characteristic, both outwardly noted on the utilisation of TD in engineering research for evidencing scientific and social impact. This is a notion which is generally raised when looking inward on the examination of TD. Although this differed slightly from the rest of the group’s responses, the perspective did not present such a degree of indifference that it justified the creation of another respondent grouping. The results and their link to specific characteristics are now discussed in turn in order of congruence as can be seen by the distribution of the respondents’ comments in Table 3.

Table 3. Distribution of respondent's congruence with TD characteristics.

Characteristic	Frequency	Percentage
1) Problem Solving Capability	12	42.8%
2) Involvement of Various Stakeholders	6	21.4%
3) Transcendence and Integration	6	21.4%
4) Unity of Knowledge	3	10.4%
5) Institutional Challenge	1	3.5%
Total:	28	100.0

4.1. Problem solving capability

In total, 12 respondents focused on the benefits of a TD approach when complex problems need to be addressed. The ‘problem solving’ characteristic provided the greatest consensus of the four characteristics.

> *Modern problems are complex and permeate different fields. Thus, by adopting a transdisciplinary approach, it is expected that merging various knowledge improves the chances of finding better solutions*. (Respondent #18).

In this theme, sub-themes emerge; Carew & Wickson’s (2010) focus on “practical problems” appeared frequently as responses emphasised the real-world application of TD research.

> *I think that TD research should be grounded to solve practical problems*. (Respondent #15).

> *It is far too easy to believe that a problem is sufficiently defined when starting for example a product design process and staying within one or two disciplines….I learned an immense amount about the complexity that comes with real-world scenarios*. (Respondent #5).

The engineering community primarily recognises the usefulness of TD from its practical applicability to complex issues. This finding supports the literature, were, to address the requirements for the inclusion of different viewpoints, authors propose complex challenges are best tackled through transdisciplinarity (Kollman and Ertas, 2010; Burritt and Schaltegger, 2014).

Whilst relevance is core to the responses, a new prominent sub-theme emerged; the utilisation of TD in research for impact.

> *TD engineering is needed, to evaluate the social and environmental impact of the introduction of technology, to innovate more diversified convenient technology through cooperation and comparison with other fields in the globalisation*. (Respondent #12).

> *TD engineering is most powerful in solving complex problems, where the impact of disciplinary-based decisions on the solution cannot be determined or assessed*. (Respondent #23).

The words “evaluate” and “assess” in the excerpts above, show how TD research could be used to evidence scientific and social impacts (Ertas, 2010; Sakao, 2019). As engineers consider not just the local, but also the global impact of their research before it is undertaken, they are perhaps more likely to adopt transdisciplinary approaches to their work (Garcia et al., 2012). Further, the impact from research is of increasing importance in the UK as it is linked to university funding (Research Excellence Framework, 2018) which has interest in TD approaches.

4.2. Involvement of various stakeholders

Six respondents focused on the need for TD engineering when researchers work with external partners. Researchers recognized they required input from that outside of academia to better understand systems and the social implications of their work.

> *TD research is necessary when you require integration of knowledge from industry, communities, regulators or other stakeholders to understand the system*. (Respondent #1).

> *TD engineering is needed in situations where an engineering solution will have a large impact on the social context in which the solution is to be used. The stakeholders of this context* [a city, a large multi-site, multi-national company, a country, the environment, etc] *need to be involved in the solution development process*. (Respondent #2).

> *The need for a TD approach would be when there are any wide-reaching societal implications that may arise from any engineered solution*. (Respondent #4).

Findings for stakeholder involvement reflect the literature's consensus on including numerous parties in the TD research approach (Carew & Wickson, 2010). Transdisciplinarity, unlike interdisciplinarity, crosses both disciplinary and societal boundaries by including stakeholders from both the private and public sectors in the development of understanding of socially relevant issues (Repko, 2009; Pohl, 2011).

4.3. Transcending and Integration

Six participants perceived TD as a beneficial approach to adopt when established engineering boundaries need to be transcended. Specifically, experts highlighted TD as suitable to span established boundaries of engineering disciplines for innovation.

> *TD research becomes more beneficial when there is a need for knowledge transfer beyond the boundaries of different disciplines*. (Respondent #17).

> *A transdisciplinary approach enables a proposal of solutions that transcend the borders and interfaces of the disciplines represented in the team, thus, providing a new view of the problem solving and thus new innovative solutions*. (Respondent #27).

Boundary spanning is not seen as adversarial, rather TD is a distinct approach that complements rather than competes with other disciplinary approaches (Balsiger, 2004). TD engineering provides a way to overcome the limitations of inter- or multidisciplinary methods (Peruzzini et al., 2020). Discipline transcendence is required for knowledge integration, which takes TD beyond other forms of disciplinarity:

> [...] *transdisciplinary goes beyond inter-disciplinary which working together with several disciplines and other external stakeholders. It will be beneficial, especially to address complex problems. Transdisciplinary will solve that kind of problem by integrating a broad set of knowledge for practical problems*. (Respondent #24).

4.4. Unity of knowledge

Three academics noted that TD as a research approach is beneficial when the unity of knowledge is needed to integrate various disciplines for a specific outcome.

> *We believe that a TD approach is a beneficial approach, rather than others when there is more than a field of knowledge that has to be studied to obtain a satisfactory result* (Respondent #11).

> *Each domain* [or discipline] *offers formal elements within the approach of another discipline, without compromising its principles, formal aspects, guidelines, components, and artefacts* (Respondent #19).

This understanding reflects notions in the general literature of going beyond the disciplines to generate knowledge (Pohl, 2011).

4.5. Institutional challenge

Whilst the rest of the group discussed the appropriateness of TD as directly applied, Respondent #22 discusses the environment of TD engineering projects that enables (or prevents) the approach from being beneficial:

> *The problem of changing the approach does not lie in the realisation of the benefits, but the organisational change of the project environment, allowing for the transition to other acceptable procedures. The term environment should be understood to mean: regulations, certification bodies, design, research and production procedures design, research and testing means and tools, etc. The potential benefits should be equivalent to or greater than the effort required to change the entire environment. It is not always a matter of the individual willing to implement such changes*. (Respondent #22).

The environment described refers to accepted customs - the process, policy and practice of the organisation. Single, multi- or inter-approaches are established ways of thinking, that are well-defined, and accepted. The ability to change established institutions may determine how the adoption rate and pathway of TD are to become (Mittelstrass, 2011). Institutional work is defined as "[...] the purposive action of individuals and organizations aimed at creating, maintaining and disrupting institutions" (Lawrence & Suddaby, 2006). For TD working to be selected and accepted as a working practice, institutional work by a collective of individuals is required to challenge and change organisations. Additionally, training in the TD perspective at the institutional level could support those wanting to actively work in a TD manner. What the institutionalisation of TD looks like is a question raised by Mittelstrass (2011).

5. Further discussion

Institutional work requires dedication towards implementation, action to change the policy environment and training at the institutional level. To achieve institutional work, TD education that establishes a common understanding needed to work in a TD way is required (Bunders et al., 2010; Schikowitz, 2021).

5.1. Transdisciplinary education

Education can ensure that the institutionalisation of TD is built up through the creation of a tradition and culture of TD in higher education, whereby, new researchers and transdisciplinary trainers of the future are educated and socialized in transdisciplinary competencies or “trans-scientific” skills that are necessary for transdisciplinary research (Kastenhofer et al., 2003; Bunders et al., 2010; Hernandez-Aguilar et al., 2020).

The desire to develop skills for TD working is evident in engineering education, where advancements in sustainable engineering have created an understanding and appreciation of transdisciplinary engineering and its subsequent education (Tejedor et al., 2018; Newnes et al., 2020). Regarding skills development for transdisciplinary engineering, technical engineering content is blended with the social sciences to develop “T-shaped” individuals, where the stem of the T refers to knowledge and expertise in one or few fields, and the top relates to broad knowledge and interest in other fields (Oyinlola et al., 2018).

One way that skills development can be achieved is project-based learning, where individuals engage in cross-disciplinary challenges embedded in professional issues (Noor, 2012; Bimpitsos and Petridou, 2012; Tranquillo, 2017; Tejedor et al., 2018). Through experience, individuals working as part of a team on a complicated development challenge solve a complex problem together (Parkes and Blewitt, 2011; Wognum et al., 2019). By emphasizing synthesis on ideas and concepts, competencies such as awareness, consciousness and communication needed to understand and collaborate with people from other disciplines are developed (del Cerro Santamarıa, 2015; Oyinlola et al., 2018; Wognum et al., 2019; Babatope et al., 2020).

As well as developing the competencies and skills, what education should aim for is to build up future engineers and researchers, so that they can consciously appreciate others. On this note, Schikowitz (2021) highlights that researchers want certainty, concreteness and normalcy: meaning, frameworks, methods, conceptual approaches and procedures which provide a common understanding of TD. However, seeking common structured processes (Schikowitz, 2021), is more characteristic of lower levels of coordination than the purpose lead TD system that accommodates multiple epistemologies (Jantsch, 1972).

Breaking this point down into a simple analogy, take for instance a group of people who wish to go to the park (shared purpose). They all agree climate change is a problem and wish to be less polluting (axiom). Person A says one route is quicker, Person B says they prefer another route as it is scenic, and Person C says they want to drive because they do not like walking. With TD, the point is not to all agree simultaneously on the same route to take together, the point of TD is being able to recognise that through coordinating the journeys, the three different people can all achieve their purpose (to reach the park), via a different means. It is realizing that Person, A, B and C could all take their routes independently of one another and still reach the same destination but through unison (walking in alignment from different positions) rather than agreement (walking altogether on the same path). Sharing axioms is what brings people together, in this instance the axiom is the different routes to take to the park without increasing pollution. The example shows how purpose and values help coordinate different disciplines in a system because with TD the agreement comes from the understanding that sometimes we will not be starting from the same perspective. Through project-based learning, we can provide students with challenges with a common purpose and shared values, that encourage TD ways of working to solve.

6. Conclusion

Differing interpretations of inter-, multi-, and trans-disciplinry research make understanding when and where TD should be employed in comparison to other disciplinary approaches difficult to identify (Faulconbridge, 2010; Lattuca & Knight, 2010; Wognum et al., 2019; Taajamaa et al., 2013). Thematically coding survey responses from TD experts against the TD characteristics in a framework built on the work of Carew & Wickson (2010), Pohl (2011) and Ertas (2010), the study has answered the question: “When might it be beneficial to take a TD rather than a single, multi or interdisciplinary research approach?”. The greatest agreement regarding the benefits of utilising TD as an approach to research comes from its problem-solving capability. There was no complete consensus over whether a TD approach is beneficial for when effective collaboration is needed, when engineering is required to redefine the frontier of natural, social, and humanities by bridging them or when standard conceptual methodologies are required to develop new knowledge (Ertas, 2010). However, the greatest agreement regarding the benefits of utilising a TD approach to research comes from the recognition that concepts, frameworks, methodologies, tools, and technologies must be shared to solve complex unstructured research problems (Ertas, 2010). The characteristics of Carew & Wickson (2010), Pohl (2011) and Ertas (2010) are all supported by our findings, except for the prominent sub-theme of using TD to evidence scientific impact. New insight recognises that whilst single -, multi-, inter- disciplinarity approaches are supported and expected ways of working, adopting a TD approach will require institutional work to develop and embed TD practices. For transdisciplinarity to become a reality in institutions, future engineers (who are the students of today) can be prepared through the development of TD competencies. Notwithstanding, at the individual level, just because one knows how to be transdisciplinary does not guarantee that one can work in a TD way or develop the competencies required to become a TD researcher or engineer. However, training and education improve the likelihood that those who do not already display TD competencies can develop them.

7. Future avenues for research

This work is limited by the small sample size and future research could address this through a larger survey. Research is necessary to develop/identify methods of TD working. To address the institutionalisation of TD working, the development of the environment in which research is conducted needs to be undertaken. Institutions are determined before work begins and will determine whether any meaningful benefits from TD are realised. We proposed that TD education is therefore important for TD engineering practice to be adopted. Research gaps exist entailing how many people are in a TD team, at what point does TD become TD ie how many disciplinary forms of knowledge does it require for someone to effectively work across, two or four disciplines? Although we addressed strategies to educate researchers and wider society from the TD perspective, work needs to be undertaken to understand which strategies are more effective than others (Hernandez-Aguilar et al., 2020).

8. References

Anselmo, A. (2018). Édgar Morin: from vicious circles to virtuous circles. *World Futures*, *74*(2), 68-83.

Augsburg, T. (2014). Becoming transdisciplinary: the emergence of the transdisciplinary individual. *World Futures*, *70*(3-4), 233-247.

Babatope, A. A., Samuel, T. M., Ajewole, P. I., & Anyanwu, O. M. (2020). Competence-driven engineering education: a case for T-shaped engineers and teachers. *International Journal of Evaluation and Research in Education*, *9*(1), 32-38.

Balsiger, P. W. (2004). Supradisciplinary research practices: history, objectives and rationale. *Futures*, *36*(4), 407-421.

Bernstein, J. H. (2015). Transdisciplinarity: a review of its origins, development and current issues. *Journal of Research Practice*, *11*, 1-20.

Bimpitsos, C., & Petridou, E. (2012). A transdisciplinary approach to training: preliminary research findings based on a case analysis. *European Journal of Training and Development*, *36*(9), 911-929.

Borg, S. J. (2021). Four investment areas for ethical AI: transdisciplinary opportunities to close the publication-to-practice gap. *Big Data & Society*, *8*(2).

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77-101.

Broo, D. G., Kaynak, O., & Sait, S. M. (2022). Rethinking engineering education at the age of industry 5.0. *Journal of Industrial Information Integration*, *25*, 100311.

Bunders, J. F., Broerse, J. E., Keil, F., Pohl, C., Scholz, R. W., & Zweekhorst, M. (2010). How can transdisciplinary research contribute to knowledge democracy? In R. in 't Veld (Ed.), *Knowledge democracy* (pp. 125-152). Berlin: Springer.

Burritt, R., & Schaltegger, S. (2014). Accounting towards sustainability in production and supply chains. *The British Accounting Review*, *46*(4), 327-343.

Carew, A. L., & Wickson, F. (2010). The TD wheel: a heuristic to shape, support and evaluate transdisciplinary research. *Futures*, *42*(10), 1146-1155.

de Jong, S. P. L., Wardenaar, T., & Horlings, E. (2016). Exploring the promises of transdisciplinary research: a quantitative study of two climate research programmes. *Research Policy*, *45*(7), 1397-1409.

del Cerro Santamarıa, G. (2015). The value of transdisciplinary collaboration in robotics education and research. *Transdisciplinary Journal of Engineering & Science*, *6*, 117-132.

Ertas, A. (2010). Understanding of transdiscipline and transdisciplinary process. *Transdisciplinary Journal of Engineering & Science*, *1*(1), 48-64.

Ertas, A. (2018), *Transdisciplinary engineering design process.* New Jersey: John Wiley & Sons.

Ertas, A., Maxwell, T., Rainey, V. P., & Tanik, M. M. (2003). Transformation of higher education: the transdisciplinary approach in engineering. *IEEE Transactions on Education*, *46*(2), 289-295.

Ertas, A., Tanik, M. M., & Maxwell, T. T. (2000). Transdisciplinary engineering education and research model. *Journal of Integrated Design & Process Science*, *4*(4), 1-11.

European Commission. (2021). *Industry 5.0: towards a sustainable, human centric and resilient European Industry*. Retrieved in 2022, August 2, from https://op.europa.eu/en/publication-detail/-/publication/468a892a-5097-11eb-b59f-01aa75ed71a1/#

Faulconbridge, J. R. (2010). TNCs as embedded social communities: transdisciplinary perspectives. *Critical Perspectives on International Business*, *6*(4), 273-290.

Garcia, J., Sinfield, J., Yadav, A., & Adams, R. (2012). Learning through entrepreneurially oriented case-based instruction. *International Journal of Engineering Education*, *28*(2), 448.

Gibbons, M., Limoges, C., Nowotny, H., Trow, M., Scott, P., & Schwartzman, S. (1994). *The new production of knowledge*. London: SAGE.

Gollakota, A. R., & Shu, C. M. (2022). COVID-19 and Energy sector: unique opportunity for switching to clean energy. *Gondwana Research*. In press.

Hirsch Hadorn, Gertrude, H. Hoffmann-Riem, S. Biber-Klemm, W. Grossenbacher-Mansuy, D. Joye, C. Pohl, U. Wiesmann, and E. Zemp. (2008). *Handbook of Transdisciplinary Research*. Bern: Springer.

Hernandez-Aguilar, C., Dominguez-Pacheco, A., Martínez-Ortiz, E. J., Ivanov, R., López Bonilla, J. L., Cruz-Orea, A., & Ordonez-Miranda, J.. (2020). Evolution and characteristics of the transdisciplinary perspective in research: a literature review. *Transdisciplinary Journal of Engineering & Science*, *11*.

Hollaender, K., Loibl, M. C., & Wilts, A. (2008). Management. In G. Hirsh Hadorn (Ed.), *Handbook of transdisciplinary research* (pp. 385-397). New York: Springer.

Hyun, E. (2012). Engineering transdisciplinarity in university Academic Affairs: challenges, dilemmas, and progress. *Transdisciplinary Journal of Engineering & Science*, *3*, 58-68.

Jantsch, E. (1972). Inter-and transdisciplinary university: a systems approach to education and innovation. *Higher Education*, *1*(1), 7-37.

Kastenhofer, K., Omann, I., Stagl, S. and Steininger, K., (2003). *Science policy for transdisciplinary research*. Encyclopedia of Life Support Systems.

Klein, J. T. (2003), Unity of knowledge and transdisciplinarity: contexts of definition, theory and the new discourse of problem solving. In UNESCO (Ed.), *Encyclopedia of Life Support Systems (EOLSS)* (pp. 35-69). Paris: UNESCO and EOLSS Publishers.

Kollman, T., & Ertas, A. (2010). Results of a survey to identify differences between interdisciplinary and transdisciplinary research processes. *Transdisciplinary Journal of Engineering & Science*, *1*(1), 117-126.

Lattanzio, S., Carey, E., Hultin, A., Asrai, R. I., McManus, M., Mogles, N., Parry, G., & Newnes, L. B. (2020). Transdisciplinarity within the academic engineering literature. *International Journal of Agile Systems and Management*, *13*(2), 213-232.

Lattanzio, S., Nassehi, A., Parry, G., & Newnes, L. B. (2021). Concepts of transdisciplinary engineering: a transdisciplinary landscape. *International Journal of Agile Systems and Management*, *14*(2), 292-312.

Lattuca, L., & Knight, D. (2010). In the eye of the beholder: defining and studying interdisciplinarity in engineering education. In *2010 Annual Conference & Exposition* (pp. 15-710), Kentucky, United States.

Lawrence, M. G., Williams, S., Nanz, P., & Renn, O. (2022). Characteristics, potentials, and challenges of transdisciplinary research. *One Earth*, *5*(1), 44-61.

Lawrence, T., & Suddaby, R. (2006). Institutions and institutional work. In S. Clegg, C. Hardy, T. B. Lawrence & W. R. Nord (Eds.), *Handbook of organization studies* (2nd ed., pp. 215-254). London: Sage.

Leach, J. M., & Rogers, C. D. (2010). Briefing: embedding transdisciplinarity in engineering approaches to infrastructure and cities. *Proceedings of the Institution of Civil Engineers-Smart Infrastructure and Construction*, *173*(2), 1-5.

McGregor, S. L. (2004). The nature of transdisciplinary research and practice. *Kappa Omicron Nu's Undergraduate Research Journal for the Human Sciences*. Working Paper Series.

McGregor, S. L. (2015). The Nicolescuian and Zurich approaches to transdisciplinarity. *Integral Leadership Review*, *15*(2), 6-16.

Menoni, S. (2006). Introducing a transdisciplinary approach in studies regarding risk assessment and management in educational programs for environmental engineers and planners. *International Journal of Sustainability in Higher Education*, *7*(3), 309-321.

Mittelstrass, J. (2011). On transdisciplinarity. *Trames*, *15*(4), 329-338.

Newnes, L., Lattanzio, S., Carey, E., Hicks, B., Nassehi, A., & Parry, G. (2020). TRansdisciplinary ENgineering Design (TREND): towards a Transdisciplinary Engineering Index. In K. Hiekata, B. Moser, M. Inoue, J. Stjepandić & N. Wognum (Eds.), *Transdisciplinary engineering for complex socio-technical systems-real-life applications* (pp. 42-49). Amsterdam: IOS Press.

Nicolescu, B. (2002). *Manifesto of transdisciplinarity*. New York: SUNY Press.

Noor, A. (2012). Emerging interdisciplinary fields in the coming intelligence/convergence era. *Open Engineering*, *2*(3), 315-324.

Oyinlola, M., Whitehead, T., Abuzeinab, A., Adefila, A., Akinola, Y., Anafi, F., Farukh, F., Jegede, O., Kandan, K., Kim, B., & Mosugu, E. (2018). Bottle house: a case study of transdisciplinary research for tackling global challenges. *Habitat International*, *79*, 18-29.

Parkes, C., & Blewitt, J. (2011). "Ignorance was bliss, now I'm not ignorant and that is far more difficult": transdisciplinary learning and reflexivity in responsible management education. *Journal of Global Responsibility*, *2*(2), 206-221.

Pasquier, F., & Nicolescu, B. (2019). To be or not to be transdisciplinary, that is the new question: so, how to be transdisciplinary? *Transdisciplinary Journal of Engineering & Science*, *10*.

Peruzzini, M., Wognum, N., Bil, C., & Stjepandic, J. (2020). Special issue on 'transdisciplinary approaches to digital manufacturing for industry 4.0.'. *International Journal of Computer Integrated Manufacturing*, *33*(4), 321-324.

Piaget, J. (1972). The epistemology of interdisciplinary relationships. In L. Apostel, G. Berger, A. Briggs & G. Michaud (Eds.), *Interdisciplinarity: problems of teaching and research in universities* (pp. 127-139). Paris: Organization for Economic Cooperation and Development.

Plumblee 2nd, J. M., Cattano, C., Bell, L., & Klotz, L. (2012). Fulfilling engineering program objectives through service learning campaigns in developing countries. *Leadership and Management in Engineering*, *12*(2), 46-52.

Pohl, C. (2011). What is progress in transdisciplinary research? *Futures*, *43*(6), 618-626.

Ramadier, T. (2004). Transdisciplinarity and its challenges: the case of urban studies. *Futures*, *36*(4), 423-439.

Rasmussen, B., Andersen, P. D., & Borch, K. (2010). Managing transdisciplinartiy in strategic foresight. *Creativity and Innovation Management*, *19*(1), 37-46.

Renn, O. (2021). Transdisciplinarity: synthesis towards a modular approach. *Futures*, *130*, 102744.

Repko, A. F. (2009). *Interdisciplinary research: process and theory.* Thousand Oaks: Sage Publications.

Royal Academy of Engineering. (2022). *APEX awards*. Retrieved in 2022, August 29, from https://raeng.org.uk/programmes-and-prizes/programmes/uk-grants-and-prizes/support-for-research/apex

Sakao, T. (2019). Research series reviews for transdisciplinarity assessment: validation with sustainable consumption and production research. *Sustainability*, *11*(19), 5250.

Schikowitz, A. (2021). Being a 'good researcher' in transdisciplinary research: choreographies of identity work beyond community. *Community and Identity in Contemporary Technosciences*, *31*, 225-245.

Scholz, R. W. (2020). Transdisciplinarity: science for and with society in light of the university's roles and functions. *Sustainability Science*, *15*(4), 1033-1049.

SCnat Knowledge. (2022), *The Swiss Academy of Sciences (SCNAT) and its network report the state of knowledge, based on sound scientific findings and in regards to Switzerland – for the attention of politics, administration, business, science and practice.* Retrieved in 2022, August 19, from https://naturalsciences.ch/

Taajamaa, V., Kirjavainen, S., Repokari, L., Sjöman, H., Utriainen, T., & Salakoski, T. (2013). Dancing with Ambiguity Design thinking in interdisciplinary engineering education. In *2013 IEEE Tsinghua International Design Management Symposium*,Beijing (pp. 353-360). New York: IEEE.

Tejedor, G., Segalàs, J., & Rosas-Casals, M. (2018). Transdisciplinarity in higher education for sustainability: how discourses are approached in engineering education. *Journal of Cleaner Production*, *175*, 29-37.

Tranquillo, J. (2017). The t-shaped engineer. *Journal of Engineering Education Transformations*, *30*(4), 12-24.

Government Office for Science. (2017). *The futures toolkit, tools for futures thinking and foresight across UK government*, Retrieved in 2022, August 16, from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/674209/futures-toolkit-edition-1.pdf

Research Excellence Framework. (2018). *Research excellence framework*. Retrieved in 2022, September 1, from https://www.ref.ac.uk

HM Government. (2020a). *UK research and development roadmap*. Retrieved in 2022, July 10, from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/896799/UK_Research_and_Development_Roadmap.pdf

UK Research and Innovation Council – UKRI. (2020). *Designing the future resilient transdisciplinary design engineers*. Retrieved in 2022, July 10, from https://gtr.ukri.org/projects?ref=EP%2FR013179%2F1

United Nations. (2022), *Peace, dignity, and equality on a healthy planet*. Retrieved in 2022, February 2, from https://www.un.org/en/global-issues

Wickson, F., Carew, A. L., & Russell, A. W. (2006). Transdisciplinary research: characteristics, quandaries and quality. *Futures*, *38*(9), 1046-1059.

Wognum, N., Bil, C., Elgh, F., Peruzzini, M., Stjepandić, J., & Verhagen, W. (2018) Transdisciplinary engineering research challenges. In *25th ISPE International Conference on Transdisciplinary Engineering Integrating (TE2018)*, Modena, Italy (pp. 753-762). IOS Press.

Wognum, N., Bil, C., Elgh, F., Peruzzini, M., Stjepandić, J., & Verhagen, W. J. (2019). Transdisciplinary systems engineering: implications, challenges and research agenda. *International Journal of Agile Systems and Management*, *12*(1), 58-89.