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Perceptions of Transdisciplinary Engineering: Characterisations of the Transdisciplinary Research Approach

Hannah GOODING[a,1], Susan LATTANZIO[b], Glenn PARRY[a] and Linda NEWNES[b]
[a] *University of Surrey, UK*
[b] *University of Bath, UK*

Abstract. Engineering disciplines are paying increasing attention to transdisciplinary (TD) working. The terminology of single, multidisciplinary, interdisciplinary and transdisciplinary lacks clarity. Consequently, there is currently no consensus on what defines a TD research approach. This makes it difficult to implement and measure the impact of TD and TD working. Clear definition of the approach and understanding of where TD is most applicable is needed because the education of tomorrow's engineers can only be realised if researchers build upon coherent theoretical frameworks. This paper draws on theory to define TD and then aims to reduce confusion and instill clarity by identifying when TD as a research approach should or should not be used. This is achieved by answering the research question: when might it be beneficial to take a TD rather than 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 institutional barriers to TD adoption may prevent the benefits of TD engineering research from being realised. Rather than the research approach itself, it is the environment in which we do our research, one which is decided long before our work begins, that will determine if any meaningful benefits from TD are realised.

Keywords. Transdisciplinarity, transdisciplinary, transdisciplinary engineering.

Introduction

Society faces complex challenges, from the impact of changing weather patterns on food production to the demands imposed on human resources from rising populations [1]. These interconnected problems span multiple boundaries. To address these interrelated challenges, expertise from multiple academic disciplines and the adoption of a transdisicplinary (TD) research approach has been proposed [2,3].

In the engineering sector, TD research approaches are increasingly being used to address emerging socio-technical concerns [3]. Despite claims that engineering disciplines have adopted TD, research approaches in the field remain understudied and within general literature, there is disagreement on which specific characteristics of transdisciplinarity distinguish it from the other disciplinary approaches [4,5]. Because there is a lack of definitional clarity, inter-, multi-, and transdisciplinarity are used

[1] Corresponding Author, Mail: hg00202@surrey.ac.uk.

interchangeably. A lack of consistency of TD research approaches [6] and conflation of inter-, multi-, and TD terms [7], creates theoretical and practical problems. The confusion of terminology makes assessing the impact of TD in comparison to "competing" approaches difficult if we do not characterise our terms [6]. Additionally, the uncertainty regarding terms that underpins the TD research approach makes it challenging to introduce TD research in engineering. As a mismatch between the principles of precision and accuracy underpinning engineering specialisms and the complexity that underpins TD research approaches occurs [8,9,10].

To understand what distinguishes TD from other disciplinarities a coherence in knowledge is needed [11,12]. Only then can we determine when and where TD is used, as well as its impact in comparison to the other disciplinary approaches [6,11,7,13]. The aim of this paper is to reduce confusion and instill clarity by identifying the predominant characteristics of TD. To achieve the aim, first; literature on TD definition and characterisation is examined. Then utilising 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? The findings reveal that context determines the appropriateness of TD adoption. Where TD adoption is appropriate institutional barriers may exist.

This paper is structured as follows. First, literature associated with TD, and TD within the engineering context is investigated (Section 1). Second, the data collection and analysis methods are presented in-depth (Section 2). The findings are given and evaluated in light of the existing literature (Section 3). Finally, conclusions are formulated and identification of future work is presented (Section 4 and 5).

1. Literature

The term "transdisciplinary" was coined at an Organisation for Economic Co-operation and Development conference in France on interdisciplinary teaching and research [14 ,15,16]. Erich Jantsch defined transdisciplinarity as: "coordination of all disciplines and interdisciplinary in the education/innovation system based on a generalised axiomatics (introduced from purposive level) and in emerging epistemological pattern." [17]. TD was seen as the academic pinnacle of disciplinary coordination, with Jantsch describing inter- and transdisciplinarity: "not as organising principles, but as steps on a rigid ladder of levels elevated to the two highest strata of knowledge" [17,18].

In the 1990s transdisciplinarity was recognised as an approach to address complex challenges such as climate change [19,20]. Two discourses emerged: the Nicolescuian and Zurich schools of thought. The Nicolescuian School aimed for a "unity of knowledge" by conceptualising TD as a disciplinarity anchored in quantum physics and complexity science [21,22]. The Zurich school, encompassed notions of practicality by conceptualising TD research and knowledge generation as developed from and focused on real world problems [23,22]. There is 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) [24]. TD is characterised as Mode 2, as research is carried out within the application's context, with knowledge generated as a result of problem-solving [25].

TD engineering focuses on fusing science and management concepts to create a unified transdisciplinarity entity for engineering design [26]. In the early 2000s TD models for education were proposed to enable the management of rapid developments in technology [26,27] including "Industry 4.0" and human-machine relationships [6,4,28].

1.1. Characterising Transdisciplinarity

The terms inter-, multi-, and TD are employed by many authors, but perceptions and understanding of what constitutes approaches may differ [5,29]. To address the challenge Carew and Wickson [30], identified characteristics of TD from research in literature (Table 1). Subsequent work, particularly in sustainable development and research policy has expanded upon these characteristics [see for example;31, 32]. In this paper we draw on Ertas [33], whose language aligns to engineering, and Pohl [5] whom proposed four main features of TD research in his "approachology" (Table 1).

Table 1. Main features of TD research.

Characteristic	Carew and Wickson [30]	Ertas [33]	Pohl [5]
1) Involvement Of Various Stakeholders		Eliminates disciplinary boundaries for strong collaboration	Participatory research
2) Transcendence and Integration	Transcending and integrating	Redefines boundaries by bridging between natural science, social science, humanities, and engineering	Transcending and integrating disciplinary paradigms
3) 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
4) 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: Pohl [5] classifies participatory research as a separate characteristic to those of Carew and Wickson's [30]. "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 [5,14]. Ertas recognises the characteristic as an enabler of collaboration.
2. Transcendence and Integration: Transcendence in TD occurs when dynamic frameworks enable collaboration between hybrid actors [30]. Collaboration is evident in multidisciplinary and interdisciplinary research, but does not reflect the search for mutual understanding amongst stakeholders inherent in TD approaches [11,34,35]. Integration in TD occurs when researchers conduct research that crosses and integrates disciplinary paradigms to solve societal challenges rather than just academic ones [5].
3. Problem-Solving Capability: The ability to solve complex societal problems is an accepted characteristic of TD [15,30]. Of the disciplinarities, only TD is

proposed as suitable for dealing with society's complex and multidimensional challenges [15,8,36,37]. Neither mono-, inter- or multi- approaches foster the collaboration and synthesis required to generate boundary-crossing solutions to complex large-scale challenges [38].

4. Unity Of Knowledge: like transcendence, knowledge unity aims to produce societally useful knowledge [5]. Understanding what? and why? characterises unity of knowledge. TD generates knowledge across disciplines [5], and there inherently cannot be a single research technique [28]. Actors share understanding through knowledge frameworks that exist in boundary-less systems where disciplinary barriers are removed [18] allowing techniques to be tailored to the environment and challenges [36]. The ability to understand the language and culture of other disciplines is more than communication; it is unity of knowledge. In mono-disciplinary approaches we learn more about individual elements, which is appropriate for specific problems, but we also know less about the whole [6,27,10]. Inter- or multi- may capture interactions between parts, but miss the global view, the uni-multiplex which tells us of the system [39]. 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 [12].

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

2. Method

The literature review on TD definitions and characteristics identified ambiguity in terminology employed. The context of TD provided by Jantsch underpins the theoretical development of this paper [17]. The work of Carew and Wickson [30], Ertas [33] and Pohl [5] was used to construct a theoretically grounded analytical framework which this paper applies in the engineering context. 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?". To identify when TD as a research approach should or should not be used, text responses were analysed using thematic qualitative analysis of Braun and Clarke [40] undertaken in six steps (Table 2):

Table 2. Phases Of Thematic Analysis Adapted From [40].

	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 theme, 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 back of analysis to research question and literature, produce a scholarly report of the analysis.

Both inductive and deductive procedures were used to prevent logical errors. Data was deductively coded against the characteristics of TD (Table 1). As Pohl's [5] "approachology" demonstrates, characteristics can display elements of multiple features at the same time, but in this paper only the dominant thesis of each respondent is reported in order to focus on differences and similarities in core understanding.

3. Results and discussion

Results from analysis of expert comment nearly all matched the characteristics from the literature (Table 1), with one respondent as an exception. The results linked to characteristics are now discussed in turn.

3.1 Problem-Solving Capability

In total, 12 academics focused on the benefits of a TD approach for 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 and Wickson's [30] 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, where, to address the requirements for inclusion of different viewpoints, authors propose complex challenges are best tackled through transdisciplinarity [8,41]. 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 [30,42]. 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 [43]. Further, impact from research is of increasing importance in the UK as it is linked to university funding [44] which has increased interest in TD approaches.

3.2 Involvement Of Various Stakeholders

Six respondents focused on the need for TD engineering when researchers work with external partners. Researchers recognised they required input from those 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 [30]. Transdisciplinarity, unlike interdisciplinarity, crosses both disciplinary and societal boundaries by including stakeholders from both the private and public sectors in the development of understanding for socially relevant issues [5, 20].

3.3 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 the purposes of 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 [45]. TD engineering provides a way to overcome the limitations of inter- or multidisciplinary methods [46]. 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.

3.4 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 [5].

3.5 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, are well defined, and accepted. The ability to change established institutions may determine how the adoption rate and pathway of TD is to become [47]. Institutional work is defined as "the purposive action of individuals and organizations aimed at creating, maintaining and disrupting institutions" [48]. 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. What the institutionalisation of TD looks like is a question raised by Mittelstrass [47]. It is likely that institutional work requires action to change policy environment, training at the institutional level, and dedicated models for implementation. Such a process will require TD education so that common understanding can be established [34,49].

4 Conclusion

Differing interpretations of inter-, multi-, and TD terms makes understanding when and where TD should be employed difficult to identify [6,11,7,13]. The ambiguity creates challenges in the consistency of engineering TD research theory and methods, and makes it difficult to compare the effectiveness of TD working to other disciplinary approaches [6]. Within this study we build on the work of Carew & Wilson [30], Pohl [5] and Ertas [33] to create a framework of TD characteristics. Thematically coding survey responses from TD experts against the TD characteristics this paper 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 the disciplinarity’s problem-solving capability. Although these findings primarily support Pohl's [5] characterisation of TD, there was still no complete consensus of opinion. Challenges remain over whether the use of a TD research approach in engineering is beneficial for 1) effective collaboration 2) when engineering is required to redefine the frontiers of natural, social, and humanities science by bridging them; 3) when concepts, frameworks, methodologies, tools, and technologies must be shared to solve common unstructured research problems; or 4) when standard conceptual methodologies are required to develop new knowledge [42].

The characteristics of Carew & Wilson [30], Pohl [5] and Ertas [33] are all supported by our findings. Novel is the recognition that knowledge creation via single -, multi-, inter- disciplinarity approaches are excepted ways of working. Taking a TD approach will require institutional work to develop and embed TD practices.

5 Future Work

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, 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 transdisciplinarity are realised. We proposed that TD education is therefore important in order for TD engineering practice to be adopted. Research gaps exist surrounding why and how certain strategies to educate researchers and wider society in the TD perspective are more effective than others [50].

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