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Using STEAM Principles and Experiences to Critique and Enhance a Transdisciplinary Collaboration Framework

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***Abstract*—STEAM interdisciplinary collaborations are essential to address complex 21st-century challenges, as they can offer new ways of learning, knowing, and collaborating with more holistic perspectives on the world. Transdisciplinary problem framing and knowledge creation can furthermore benefit deep and applied learning and guide projects. However, setting up teams across academic disciplines and practices to achieve meaningful and effective outcomes is challenging, and a coherent framework and repeatable approach could aid in their success. Today, no framework for STEAM collaborations addresses the entire collaboration cycle between project partners from diverse academic disciplines and non-academic backgrounds to systematically achieve transdisciplinary knowledge creation. This study presents a STEAM evaluation of a general framework for conducting transdisciplinary research (TDR) in three phases: TDR initiation, TDR management, and transdisciplinary knowledge exchange. This STEAM evaluation was based on the researchers' experience and network of STEAM research and recent projects. A particular focus in this paper is to share insights into the challenges faced by diverse disciplinary collaborations with engineering students and engineers in achieving transdisciplinarity and how a STEAM lens to a TDR framework may help to prepare for or overcome these challenges. The study is expected to contribute to the development of a comprehensive framework for STEAM collaborations that could be used by researchers and practitioners to achieve transdisciplinary knowledge creation, be that in their research or teaching.**

Keywords—STEAM, framework, transdisciplinarity, interdisciplinarity, integrative, knowledge creation, epistemology, diverse team, transdisciplinary research, transdisciplinary collaboration, arts, engineering education

I. INTRODUCTION

Typically, cross-disciplinary collaboration projects are managed the same way regular projects are, neglecting the challenges of bringing diverse disciplines together. Stumbling blocks include differences in values, perspectives, research cultures, priorities and pressures in terms of outputs and funding [1]. Current endeavors under the STEAM (acronym for science, technology, engineering, art, and math) umbrella have gained traction and may be of particular interest to engineers and engineering educators striving for transdisciplinary research (TDR) and education. According to Bertrand & Namukasa [2], a STEAM approach to learning achieves both disciplinary and beyond discipline skills, especially critical thinking, problem solving, creativity, and innovation within a collaborative and communicative setting. The A in STEAM includes diverse disciplines within the overarching labels of arts, humanities, and social sciences and often adopts a design-based (or design-thinking-based) and creative process. Recently, explicit attention has been paid to the range of STEAM approaches and methods in higher education and their specific characteristics and expected benefits [3][4][5]. Furthermore, especially for primary and secondary education and teacher training, competencies (cognitive, personal, and interpersonal), didactic approaches, curricula, programs, and assessments have also received widespread attention. However, less specific and critical attention has to date been given to the overarching process and specific stages of a typical STEAM project. This leaves the success of the coming together of disciplines to chance. For example, having and building trust is critical to successful team dynamics but not explicitly highlighted or addressed in STEAM frameworks today.

There are thus many important aspects to facilitate effective and insightful collaborations across disciplines, among others, the awareness of different epistemologies, creating meaningful conversations and sharing understanding of ideas and goals unhindered by discipline-influenced lexicons and theories. The process, provisions, and power-sharing allow exploration and new angles of looking at a problem to emerge so that a collaboration can become more than the sum of its parts. Much can be gained from eliciting and addressing such key aspects to increase benefits from transdisciplinarity and reduce the element of chance for successful encounter of various disciplines and knowledges. While we are aware that important lessons can also be learned from TDR and projects that have encountered many challenges and even failed [1] in education and for gaining research funding, affirming experiences and success in achieving meaningful and memorable outcomes or

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outputs can be key to success and lead to more enjoyable experiences and tangible benefits for society.

II. Background

With society facing increasingly complex problems, cross-disciplinary teams are required to seek global solutions [6]. STEAM and other pluridisciplinary collaborations are essential to address complex 21st-century complex challenges, as such collaborations can offer new ways of learning, knowing, and working with more holistic perspectives on the world. Engineering and other disciplines must learn to work in and lead cross-disciplinary teams to achieve transdisciplinary knowledge creation and envision new elements of solutions. STEAM and other cross-disciplinary methodologies help bring diverse disciplines together in work and educational settings. Transdisciplinary problem framing and knowledge creation can also benefit deep and applied learning and guide projects.

However, setting up teams across academic disciplines and practices for achieving meaningful and effective outcomes is challenging [1]. A coherent framework and repeatable approach could aid in their success. Today, no framework for STEAM collaborations addresses the entire collaboration cycle between project partners from diverse academic disciplines and non-academic backgrounds to systematically achieve transdisciplinary knowledge creation.

Based on two decades of experience with STEAM work in classrooms of artists and engineers and other TDR, the authors have concluded that the achievement of transdisciplinary knowledge creation in a cross-disciplinary team fundamentally depends on the human factors involved in the team and engagement with the process. In this study, we are looking to develop a holistic model that will address the methodological and the human factors challenges of such endeavors. This paper presents a STEAM evaluation of a general framework for conducting transdisciplinary research in three phases: TDR initiation, TDR management, and transdisciplinary knowledge exchange (TKE) [7]. This STEAM evaluation was based on the researchers' experience and network of STEAM research and recent projects.

A particular focus in this paper is to share insights into the challenges faced by diverse disciplinary collaborations with engineering students and engineers in achieving transdisciplinarity and how the adapted framework may help to navigate or overcome these challenges. The study is expected to contribute to the development of a comprehensive framework for STEAM collaborations that could be used by researchers and practitioners to achieve transdisciplinary knowledge creation, be that in their workplace, research, or teaching. The findings of the study are, however, of wider relevance and will be of interest to professionals and academics from diverse backgrounds who are interested in cross-disciplinary collaborations and transdisciplinary research.

The following section explains the intellectual reference points for our evaluation of Butt and Dimitrijević's transdisciplinary framework understudy concerning the importance of cross-disciplinary friction in achieving transdisciplinary knowledge creation and how we define our STEAM lens and methodology. Then, we present the Transdisciplinary Collaboration Framework that we explored and evaluated.

A. Cross-Disciplinary Friction

Philosophers Bruno Latour and Isabelle Stengers offer insights on cross-disciplinary collaborations and transdisciplinarity. Latour [8] argues that recognizing different forms of knowledge can help to overcome the divide between science and society. He advocates for a more collaborative and open approach to knowledge production, where different forms of knowledge are recognized and integrated into decision-making processes. This approach can help to build trust and credibility between experts and non-experts and can lead to more effective and lasting changes to address complex problems.

Isabelle Stengers [9], a Belgian philosopher of science, has made significant contributions to the field of transdisciplinarity. One of her key notions is "écologie des pratiques" or "ecology of practices", which is a framework for understanding the complex and dynamic relationships that exist between different fields of knowledge and different actors in society. This approach challenges traditional notions of science and expertise, which often view knowledge as something that is produced by human beings in isolation from their environment.

Stengers [10] also argues that friction is necessary for fruitful interdisciplinary or transdisciplinary collaborations. According to her, when experts from different fields come together, they should engage in a kind of dialogue that recognizes the inherent incompatibilities between their assumptions and methodologies. This clash of perspectives can be unsettling, but it is necessary for producing new insights that transcend any one discipline. Friction, then, can be seen as a productive force that drives new perspectives and encourages critical thinking. In the same vein, Stengers [10] suggests that a lack of friction can lead to superficial collaboration and lack of progress. Therefore, while friction can be uncomfortable, Stenger emphasizes the importance of embracing and valuing friction and argues that it is essential for achieving meaningful progress in collaboration.

Transdisciplinary knowledge creation thus most likely happens through the exploration of the zones of friction. Differences (in perspectives, preferences, theory, methods etc.) are thus seen as something 'normal' and enriching rather than something that needs to be avoided or overcome. Working collaboratively with or through divergent viewpoints and the curiosity to better understand differences helps shape new ways of perceiving and doing, and deepens and widens understanding.

B. Transdisciplinary Collaboration

There are multiple ways for cross-disciplinary research collaboration to happen: multidisciplinary (MDR), interdisciplinary (IDR), or transdisciplinary (TDR). Researchers tend to collaborate for mutually beneficial research purposes and may be involved in one or more of these cross-disciplinary ways of working and thinking. MDR

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involves different disciplines working independently towards a research goal that can be additive, not integrative. IDR takes advantage of a more integrative approach where researchers from different fields work together from the start to frame the challenge and shape the methodological approach and through that process learn from each other's expertise but also start experimenting with and transforming their own practice (akin to some blurring of boundaries). TDR happens when researchers go beyond their disciplines to include non-academic knowledge holders and actors, exploring novel or hybrid methods and breaking with some disciplinary conventions to create a shared framework, viewing the world holistically without being a new discipline [7], [11]–[13]. This is the type of cross-disciplinary collaboration that this paper aims to improve.

Importantly, TDR is grounded in a premise whereby socio-political awareness, ethical and moral considerations matter, fresh ways of interaction happen, and new knowledge emerges. TDR thus acknowledges the input from, but advocates going beyond, disciplinary theory, methods, and approaches. It encourages thinking, knowledge, and inquiry in new ways [14]. Durall et al. [15] tried to capture these differences in diagrammatic form in the context of STEAM transdisciplinary working, illustrating how adopting a genuine transdisciplinary lens dissolves some traditional boundaries and transcends stereotypical ways of working to transform participants in their ways of being, thinking, interacting, learning, and doing.

C. STEAM Principles

According to Article 5 of the Charter of Transdisciplinarity [16], TDR goes beyond the "exact sciences" capable of accurate quantitative expression and includes a dialogue with, among others, the humanities, social sciences, and art. STEAM, akin to the interpretations and applications of transdisciplinarity, shows significant variation and differences in underlying drivers with resulting ambiguities and tensions (see e.g. [3]). As part of the Erasmus+-funded STEAM INC project (http://steaminnovation.org/about/), a group of European STEAM-active universities and institutions sought to provide some clarity in identifying key principles for STEAM in higher education. Drawing on the wide range of experiences of the project partners, the following working definition emerged, capturing key principles as [3, p. 11]:

"Involving a culture (or cultures) that puts the Arts and Sciences on an **equal** footing; operating within a paradigm that is **process-driven**, student-centered, holistic and provides permission to fail alongside being comfortable with uncertain end-results; being **collaborative**, diverse and delivered through safe spaces; establishing a mindset of **radical openness**, flexibility, reflection, experimentation and **curiosity;** generating qualities that **promote learning**, cooperation and multi-modality; supporting practices that are transdisciplinary and emphasize **prototyping and making** whilst considering modes of assessment; developing competencies of **critical thinking**, creativity and communication whilst investigating how these can be applied to generate solutions."

STEAM is inherently inter- or transdisciplinary, and understanding the role of the "A" (arts) is important. The above quote highlights the need for "an equal footing", but there is more to it. Anyone trained in the arts (including the whole range from fine art to visual culture, music, performing arts, and design) will have experience of "epistemic shifting" [17], i.e., drawing on different disciplines to define problems, create knowledge, and develop or apply processes. This is not, or at least less, the case for students and professionals trained in STEM subjects, the humanities, or social sciences with a discipline-specific theoretical and methodological focus; even though in teaching the arts a specific disciplinary "code" or process may be followed (e.g., a design thinking process or an arts-based inquiry).

D. A Transdisciplinary Collaboration Framework

After circa 20 years of working on achieving transdisciplinary knowledge creation with various teams, the authors observed that some basic human needs (such as the need to feel secure and safe) are important for team members to collaborate openly and efficiently. A Transdisciplinary Collaboration Framework was presented and validated by Butt and Dimitrijevic [7], in the context of nature-based design of sustainable built environment. This framework offers an approach to TDR projects that considers some of those human elements. In this study, we seek to evaluate their framework to explore its suitability for STEAM transdisciplinary collaborations.

The framework for conducting TDR proposed by Butt and Dimitrijevic [7] has three main stages: TDR initiation, TDR management, and transdisciplinary knowledge exchange. Each stage has three associated stages with the respective type of learning and outputs suggested for each. TABLE 1 TABLE 1. TDR PHASES AND SUGGESTED OUTPUTS FROM BUTT AND DIMITRIJEVIC [1]presents the TDR phases, their associated stages, and suggested outputs [1] which we revisit in detail in our evaluation section but offer a general description here.

TDR Initiation Stage: The TDR initiation stage includes three associated stages. First, the skills development stage explores the initial thinking and needs of participants, the way a group will function in terms of its learning environment, thinking skills, communication, empathy, and training on how to conduct interdisciplinary research. Second, the context and stakeholder identification stage establishes the specific context for research, considering the specificity of the stakeholders involved. It also suggests the role of principal investigator as responsible for creating the sub-teams of scientific and other participants, using "concepts such as tie strength, perceived trustworthiness, and receipt of beneficial knowledge" [7]. Third, the **problematization** stage entails the creation of a common ground and common language for joint problem formulation and project design. It also covers boundary management, conflict mediation, and communication tools.

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TABLE 1. TDR PHASES AND SUGGESTED OUTPUTS FROM BUTT AND DIMITRIJEVIC [1]

TDR Phase and Suggested Outputs		
TDR Phase	***Associated stage and actions***	***Suggested outputs***
1. TDR initiation	1.1 Skills development	1.1.1 Recommendations on collaborative learning environments, responsible research, and innovation and interdisciplinary working
	1.2 Context and stakeholder identification	1.2.1 Diagrams: innovation ecosystems (1) and finalized combination type of scientists/researchers for interdisciplinary research teams of the TDR project (2)
	1.3 Problematization	1.3.1 Formulated joint TDR problem
2. TDR management	2.1 Transdisciplinary boundary management and TDR problem dimensions	2.1.1 Diagrams: scientific, international, and sectoral dimensions of the TDR problem (1) and stakeholder mapping (2)
	2.2 TDR project co-planning and co-management	2.2.1 Overview of key lessons learned: case studies based on multidisciplinarity, interdisciplinarity, and transdisciplinarity (1), the Gantt chart of upcoming activities (2), and evaluation criteria for the TDR project (3)
	2.3 TDR conceptual framework development and refinement	2.3.1 A TDR framework for the project on which the team will collaborate
3. Transdisciplinary knowledge exchange	3.1 Engagement of higher-education institutions and wider public	3.1.1 Summary of the outcomes of engagement with the public (1) and a summary of the outcome of engagement with higher-education institutions (2)
	3.2 Transdisciplinary knowledge integration	3.2.1 A diagram showing hierarchical levels of transdisciplinarity of the TDR project (1), systematic reviews of related work (2), and co-authored draft papers for TDR dissemination (3)
	3.3 TDR dissemination and training for academic and non-academic community members	3.3.1 Training and development plan (1), summative evaluation criteria (2), and summative evaluation of transdisciplinary knowledge exchange processes (3)

TDR Management Stage: TDR management includes the following three associated stages: 1) **Transdisciplinary boundary management and TDR problem dimensions** consist of managing differences that may damage partnerships, understanding collaborative forces, and demarcating problems and their sectoral dimensions for resolution. 2) **TDR project co-planning and co-management** focuses on how the cooperation of participants would be implemented, organized, and managed. 3) **TDR conceptual framework development and refinement** includes refining the conceptual frameworks, mapping contributions of each discipline, and establishing a network of stakeholders.

Transdisciplinary Knowledge Exchange: The transdisciplinary knowledge exchange stage is composed of three associated stages. First, the **engagement of higher-education institutions and the wider public** includes nurturing stakeholder relations, achieving community consensus, and implementing various social experiments. Second, the **transdisciplinary knowledge integration** stage needs interaction between arts and the humanities and the use of formal and informal knowledge processes. It also needs co-production processes bringing together different knowledge types across the science–society interface. Third, **TDR dissemination and training for academic and non-academic community members** focuses on the increased diversity of knowledge required for solving complex societal problems with the support of academic and non-academic urban knowledge producers. Transdisciplinary knowledge exchange relies on community-owned solutions, achievements of community peer-to-peer knowledge, and summative evaluation of knowledge transfer processes.

Using the following methodology, the components of this framework are examined to evaluate their validity and potential adoption in a STEAM transdisciplinary context.

III. METHODOLOGY

The research methodology for this paper draws on social learning and reflective practice in co-productive contexts of working (teaching, research, continuous professional development). Our underlying theoretical learning environment paradigm aligns with social constructivism and critical realism. Specifically, Jonassen's [18] eight characteristics of social constructivist leaning environments (see TABLE 2) illustrate the plurality of perceiving and engaging with reality that can be found in different communities of inter- and transdisciplinary practice (be they within and between academic disciplines or the range of practitioners, policy-makers and decision-makers) and different cultural and historical contexts (in our case, present-day Canadian and UK/European). In the context of ongoing climate and ecological emergencies, our critical realism ontology means that while multiple perceived realities exist, there is also a material reality that we must strive to connect with, understand, and act on/with. Thus, a critical realist approach probes into the theories and practices of the sciences and social sciences (and their critiques), is sensitive to ethics and to changes in thinking, and promotes non-duality [19].

Methods of reflective practice [20][21] included critical analysis of self and participants in TDR projects and teaching (underlying values and worldviews, motivations, conceptualization, behavior) in an experiential learning and

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doing context, conducting experimentation and using rapid appraisal techniques. While we have notes and writings to bring some of the reflections and learning to the fore, for this article we used a discursive approach (weekly 1.5-hour online meetings over the six-week writing period) that then helped inform the structure, focus, and content of this paper and any actions in between those meetings. In doing so, we drew on the memory of our reflective practice and learning over the past 20+ years, identified and conducted additional reading including sources that informed the initial TDR framework [1], and brought into play past and current discussions with other TDR participants and critical friends (e.g., engineer colleagues; design-focused and architecture colleagues interested in sustainability). Such a personal mixed-methods approach may arouse some concern over robustness, especially if a researcher leans towards positivist ways of conducting and presenting research; yet the arts-related disciplines and social sciences have over the years developed peer-reviewed methods and critical analytical processes (as outlined above) that help elicit and understand underlying values, motivations, connections and causes, and a sense-making of past and present social-ecological systems and our academic context and reality. (An example dealing with such methodological critiques and myths and forging new thinking in methodology endeavors is Jessica Smartt Gullion's book *Diffractive Ethnography* [22].)

TABLE 2. SOCIAL CONSTRUCTIVIST PRINCIPLES THAT ARE PERTINENT FOR TRANSDISCIPLINARY PROJECTS AND LEARNING ENVIRONMENTS [18]

	Social Constructivist Principles
1.	Allow multiple representations of reality.
2.	Avoid over simplification and represent the complexity of the real world.
3.	Emphasize knowledge construction instead of knowledge reproduction.
4.	Use authentic tasks in a meaningful context rather than abstract instruction out of context.
5.	Use real-world settings or case-based learning instead of predetermined sequences of instruction.
6.	Encourage thoughtful reflection on experience.
7.	Enable context- and content-dependent knowledge creation
8.	Support collaborative knowledge creation through negotiation, not competition for individual recognition.

IV. FINDINGS AND IMPACT ON ENGINEERING EDUCATION

A. Evaluation

With the objective of contributing a framework for STEAM collaborations that addresses the entire collaboration cycle between project partners from diverse academic disciplines and non-academic backgrounds to systematically achieve transdisciplinary knowledge creation, we evaluated Butt and Dimitrijevic's [7] framework for conducting TDR in relation to STEAM projects and methodologies. We reviewed how the STEAM principles and approach apply or not to the framework under study.

We report our findings on the evaluation of the framework by first giving our overarching evaluation of the TDR model. Then, we consider each of the three main framework stages: TDR initiation, TDR management, and transdisciplinary knowledge exchange TKE, along with their three associated sub-stages of respective types of learning / action, and outputs. Finally, we present our recommendations about the value of the TDR framework in a STEAM transdisciplinary context. We would like to emphasise that while a detailed analysis was carried out examining each sub element of each phase in a comparative table, the presentation and discussion of results here only picked some elements where STEAM principles would further enhance or change the focus of specific stages and elements of the TDR framework studied.

1) *Overarching Evaluation*

Overall, we found the framework, and specifically the inclusion and detail for the initiation phase, a rich resource and useful framework. However, here we focus on pinpointing aspects we found potentially problematic for STEAM TDR contexts.

The TDR framework is presented as a **linear model**, with the project process flowing from one stage to the next, each stage including some actions and outputs. The stated focus is on facilitating the integration of diverse cross-disciplinary knowledge and perspectives for the purpose of working on nature-based solutions in the built environment. While being a systematic approach that progressively enables development and refinement, the framework lacks explicit feedback loops and cyclical or iterative processes for the overall TDR project process and specific parts within a stage. STEAM processes do not necessarily follow a set way of steps and hence would allow for iterations and feedback loops to occur within an "organic", creative process[23].

Similarly, **establishing common ground and being consensus oriented** as an overriding goal from the start, as indicated in the TDR framework, can be problematic and limiting. It also diverges from STEAM principles of being radically open to new knowledge, ways of thinking, and perspectives (and not being on the defensive), as well as being curious and imaginative while retaining a critical mind and humility about one's own experiences and knowledge in the process; thus, being open to potentially shifting one's mindset considering such new knowledge and experience. A focus on common ground also misses the potential benefits of friction (as already indicated above with reference to the works by Stengers). Differences in perspectives and thinking when elicited and being part of the research discussions can lead to deeper learning and new forms of enquiry rather than forcing the finding of middle ground or a common (often lowest) denominator. STEAM processes based on design thinking typically would require a phase of brainstorming and quickly testing many ideas (using a "fail-fast" formula [23]) rather than forging consensus and limiting consideration of alternatives very early on.

While some elements in the TDR framework may be problematic from a STEAM perspective, the explicit inclusion in the framework of an initiation phase is a notable strong point. It is an important aspect and one that seems neglected

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(absent, minimal, or done quickly) in, or when talking about, STEAM projects and processes. It was also one of the factors that sparked our interest in delving into this TDR framework more deeply.

2) Evaluation of the Three Main Stages: TDR Initiation, TDR Management, and Transdisciplinary Knowledge Exchange

The **TDR initiation** stage is an explorative phase to assess differences (personal and professional) and develop a common conceptual base. The TDR framework puts onus on the principal investigator to initiate and facilitate the success of this stage with the co-investigators. This indicates a distinct leadership role (the norm in traditional research funding). In contrast, in STEAM projects and approaches, a shared, or distributed, leadership model and flat structure is common in research and higher-education contexts, the emphasis being on responsibility being shared and equality of voice given to different disciplines and experiential backgrounds within the collaborative effort.

A key ingredient in the success of collaborative projects resides in the already existing or forming of trust between team members. The TDR framework highlights trust and particularly draws on Levin and Cross's [24] work highlighting benevolence- and competence-related trust, as well as the formation and level of trust affecting knowledge exchange. Professional-level trust relates to the specific work (arguments and ideas, etc.) contributed to a TDR project but may also relate to personality and contextual factors such as space or past experiences. Maslow's hierarchy of needs [25] is relevant here for considering participants' needs in the choice and design of spaces, methods, and formal and informal communication in TD, and motivational factors for collaboration, advancing learning and self-actualisation. In a collaborative context, Maslow's level 1 of physiological needs draws attention to the presence of a welcoming and safe physical or virtual place for interaction. However, feeling secure is not just a matter of having a physical safe space but also feeling secure through group intactness and building of trust (Maslow's level 2) and how these spaces facilitate and support links between participants [26]. Group security is furthermore related to external factors that bring the group together, such as funding (including stability in continued funding) and institutional support, as well as the degree of self-organisation and each member's connectedness with the collaborative effort [27]. Social relationships among team members are thus critical (Maslow's level 3). Esteem (Maslow's level 4) equates to developing a sense of each person's strengths and the perspective they contribute to the team [28]. It necessitates recognizing the value of different disciplinary and experiential or user perspectives. The equivalent of self-actualization (Maslow's level 4) in a collaborative context is team actualization. Team actualization occurs when different perspectives are recognized and valued, and the team has evolved to accommodate the different perspectives into a shared vision [29].

Another important aspect is whether or how one judges others. In our experience with STEAM collaborations, these considerations and experiences point to a different type of trust that is also significant: that of trusting the process and the group of participants, putting worries, prejudice, or set expectations of someone aside and approaching the process and all its participants with respect and good will. Working in groups usually includes some differences in character, opinion, preferences, reference points, and so on. Participants and managers of TDR may underestimate the existence and importance of such differences and friction. In STEAM collaborations, consensus is not necessarily needed to progress with the next steps. The shared experiential learning offers another level of understanding that comes from the senses. Adopting a critical, rather than judgmental, mindset and letting some friction exist, in our experience, has led to challenges dissolving with time and the outcomes or outputs of the process being beyond one's initial expectation and imagination. Trust, therefore, relates not only to relationships but also to the process and given context.

Tejedor et al. [26] in their study of 22 different transdisciplinarity implementations in engineering education, state that Transdisciplinarity is a required competence for technical programs, however engineering educators find it challenging to address the social sciences and humanities training involved. Tejedor et al. [26] also observe that engineers excel at being skeptical and questioning dominant axioms and assumptions to reformulate things; however, there is a need for "a cognitive flexibility manifested in a willingness to see beyond one's own discipline" [30, p. 36]. Tejedor and colleagues also found that engineers would benefit from alternative knowledge and perspectives arising from different ways of knowing. So doing, it would lead "to critically thinking engineers who reflect and rework public welfare construction and understand natural cycles and technological systems management".[7]

In our experience, the social sciences and humanities training is key to gain openness to new ways of knowing. The introduction of workshops on social sciences and humanities, like proposed in Butt and Dimitrijevic's [7] framework, is a good way to present the information, however, it provides short term and punctual exposure to new skills which are presented outside the natural project environment. It does not guarantee a lasting impact throughout and after the project. A STEAM approach brings those social sciences and humanities notions within and throughout the project via specific methodologies or diverse individuals with different ways of thinking and knowing. This ensure that new approaches are used throughout the project and bring about lasting cultural changes in a natural learning environment.

Another important component of the initiation stage is the attention given to knowledge ecosystems, signifying the interconnections among individual, group, internal, and external relationships, as well as processes and the supporting environment. This kind of complex systems thinking has been highlighted by some authors and is pertinent to STEAM projects, teaching, and learning[31]–[33]. Viewing TDR collaborations as knowledge ecosystems also corresponds to Stenger's perspective on "ecology of practices" [9].

The **TDR project management** subphase (of the **TDR management phase**) focuses on how the cooperation of participants would be organized, and managed. This part takes a strong theoretical perspective in explaining the specific

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substages and components. Overall, we found this phase had similarities to how many STEAM projects and processes tend to be approached and reported in the literature [34][35], and hence we have fewer specific comments for this stage.

A key observation, and a point of critique, is that the described process flow focuses strongly on drawing boundaries and clear demarcation for topic, scientific, and sectoral dimensions and for participants and stakeholders. These boundaries are further emphasized by also trying to anticipate and manage any potential differences that are perceived to risk damaging the working relationships or endangering the successful running and conclusion of the TDR. Challenges and failures in inter-disciplinary and transdisciplinary working are plentiful, if rarely documented (with some notable exceptions, [1]) and hence understandably a key issue in this TDR framework which was derived in parts from the literature and experiences but not from STEAM-specific projects. However, from our (less conventional, egalitarian, and disruptive end of the spectrum of) STEAM project experiences and interpretation, the TDR framework seems to be a very managed rather than a more organic, trusting, and self-/group-motivated process. As a result, it may be harder to cross existing barriers and tackle challenges by operating in this traditional mode of thinking and collaboration. Good management can go a long way to providing an enjoyable project journey. However, if imagination and innovation are sought, then a more critical and spontaneous approach could help achieve unconventional transformative collaborative experiences, thinking, and outputs.

Project evaluation is listed as one of the key stages as part of TDR project management and is an essential component of any funded project and of reflective practice. Here the linear framework model seems particularly unhelpful. Ideally, any evaluation should be embedded and happen right from the start through to the end of a project and beyond (as now demanded, for example, by funding bodies including UKRI, the UK's national research and innovation funding body, which require annual updates on measuring impact of projects for a period of five years post end-date). Embedding reflective evaluation helps uncover unexpected opportunities, bringing to one's consciousness subtle or emerging behaviours, issues, and changes, and therefore adds to critical thinking and agency. This may also partly explain why friction is seen less as a problem and more as a positive part of TDR.

The **TDR conceptual framework development and refinement** subphase (of the **TDR management phase**) suggests a continual refinement of conceptual frameworks and the formation of interdisciplinary research teams. This subphase seems very specific to the researchers' purposes, but also suggests an iterative approach at that level which corresponds to a STEAM approach.

The third and final stage, **transdisciplinary knowledge exchange**, again shows many parallels in thinking we observed in STEAM projects. Relationships here are key: how to nurture and facilitate, convene, and mediate them. An interesting point made is that "Knowledge transfer is much less effective than knowledge co-production as it needs knowledge interfacing and sharing, shifting from viewing knowledge as a transferrable element to viewing knowledge as a process involving negotiation among all participants" [7, p. 8]. This highlights the importance of experiential learning and arts- and design-based scoping, and so communication methods may bring additional benefits in making TDR knowledge and project outcomes more tangible to a wider audience but also more memorable and motivating for project participants.

3) Recommendation on Validity and Potential Adoption in a STEAM Transdisciplinary Context.

The TDR initiation stage offers a setup that is not typically reported on STEAM processes in the literature, which tends either to be more curriculum and didactic based or to include case studies focused on project management and outcomes portions and does not explicitly engage with or discuss the initiation process as a key component.

TABLE 3 highlights key points of our critique comparing the added dimensions, gaps, and differences in the assessed TDR framework with that of a typical STEAM project and what this may mean in terms of consequences in research and teaching. The first two columns on the left list the main three TDR stages with their respective three sub-stages, including a characterization of the overall process/framework. The middle column then lists characteristics to highlight the ways in which a STEAM-adapted TDR framework would differ or what it would add. In the right-hand column, we provide examples of what the STEAM-TDR framework's added value would be in terms of process, outcome, and outputs, using an engineer, engineering educator, or engineering researcher as the point of focus. In principle, similar benefits and impacts could apply to other disciplines.

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TABLE 3. EXPLORING THE DIFFERENCES AND COMPLEMENTARITIES BETWEEN BUTT AND DIMITRIJEVIC'S TDR FRAMEWORK AND A STEAM ADAPTED VERSION AND THEIR IMPLICATIONS FOR ENGINEERING PROJECTS, RESEARCH, AND EDUCATORS

TDR Framework (Butt and Dimitrijevic)		**STEAM Characteristics Adapted Framework (based on** [3] **and authors' experience)**	**Comments/Significance for Engineering (authors' assessment)**
Overall Process Mapping	Linear	Linear *and* iterative; design thinking style (e.g., double diamond) flow of diversion and conversion phases	Structured approach with some iterations and feedback loops that can be followed step by step but may require some facilitation or support
	Planned	Planned or organic way of working	New or different framework to traditional, predominantly positivist, way of working
TDR Initiation	Skills development:	Cognitive shifts / extension (within and beyond own disciplinary knowledge), intra- and inter-personal skills development; experiential rather than recommendation based	Engineering knowledge and skills are but one among many; unlearn as well as learn
	Context and stakeholder identification	Context is important and needs investigating from different disciplinary and experiential and/or user perspectives	Collaboration goes beyond the established team of collaborators, casting participation and perspectives more widely. Must include users and/or user perspectives
	Problematization: joint TDR problem	Of the possible problem definitions, several may be scoped before one is chosen to be taken forward in detail	Problem definition is brought into focus for critical examination and discussion rather than pre-judged/assumed.
TDR Management	Transdisciplinary boundary management and TDR problem dimension	While some boundaries decided, some flexibility maintained throughout; focus decided yet diversity of perspectives invited	Looking beyond project boundaries and zooming in and out to consider issues at different scales
	TDR project co-planning and co-management	Inter- and transdisciplinary (rather than multi-disciplinary) working; evaluation based on criteria rather than pre-determined outputs	Different ways of working compared to disciplinary and multi-disciplinary teams; participants are taken out of their comfort zone
	TDR conceptual framework development and refinement	Distributed leadership or no leader per se and shared responsibility	Challenges traditional roles such as project lead and experts in charge of distinct aspects to a more shared and organic way of collaborating throughout
Transdisciplinary Knowledge Exchange	Engagement with higher-education institutions and wider public	Process, learning, and actions emphasised over written and/or static outputs	More multi-dimensional working and learning and presentation of ideas and progress; target may stay indeterminate or flexible for longer
	Transdisciplinary knowledge integration	Less focus on hierarchies and more focus on connections and assemblages	Project becomes more complex and objectives wider reaching
	TDR dissemination and training for academic and non-academic community members	Potentially developing prototype; wide variety of outcomes and outputs—not all necessarily tangible	More diverse and/or multi-functional designs or solutions

B. Impact on Engineering Education

We hope the findings of this study will be of interest to professionals and academics from diverse backgrounds who are interested in cross-disciplinary collaborations and transdisciplinary research. With this preliminary critique, we wish to prompt curiosity and critical reflection by researchers engaged in cross-disciplinary research and engineering (and other) educators, as well as an appetite to explore STEAM principles and approaches in their work. Furthermore, we want this initial critique to help highlight what we have experienced as being fundamental—yet commonly overlooked—phases and needs of TDR, especially in current policy drives to embrace STEAM-based education and applied research.

More specifically, we believe the findings in the study can benefit engineering education in several ways and present a few here.

The authors have experienced that different types of engineering (civil, mechanical, computer, environmental, bio-technical, etc.) are significantly different and specialized, so they could be viewed as essentially functioning as different disciplines. Therefore, as a first important step within the engineering profession, bringing together various types of engineers on a project may be experienced similarly to bringing various disciplines together, like in STEAM or transdisciplinary collaborations. The lessons learned in STEAM and TDR framework presented here, could be applied to engineering education to train them for multi-engineering projects and ideally in inter- and transdisciplinary collaborations beyond the engineering profession (such as: ethicians, psychologists, lawyer, etc.) to include wider stakeholder and user perspectives. For example, the notions introduced in the TDR initiation phase (such as establishing personal and professional trust, hierarchy of needs of the team to become highly performing, understanding the complexity of the knowledge ecosystem existing within the group, etc) could be introduced in engineering design courses to train future engineers to negotiate the unavoidable and desirable differences and frictions as they emerge.

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Another element covered in the TDR Initiation stage is the establishment of common ground and the challenges involved in transdisciplinary collaborations [25]. Establishing common ground can be challenging in cross-disciplinary collaborations, as each discipline refers to a very different conceptual framework. Mastering strategies to establish common ground or to negotiate situations where no common ground can be found and friction remains, is key to generating new transdisciplinary knowledge. Placed in those situations, we could hope that self-motivating individuals in the group would find ways to work with or overcome these differences, for example by following good practices as postulated for STEAM or TDR. Training future engineers on TDR best practices would best prepare them for transdisciplinary teams required to address complex and contested social-ecological problems.

Over our years of experience in using STEAM approach in engineering projects, we have witnessed the openness in new ways of knowing and empathy towards the other. Adopting specific STEAM methodologies or including team members with diverse viewpoints from social sciences and humanities bring about lasting cultural changes in a very natural learning environment. And we concur with Tejedor et al. that STEAM could have a major impact on engineering education: "if engineering programs are able to challenge transdisciplinarity, then they may be able to train a different kind of critically thinking engineer, who reflects on and rewrite the co-construction of public welfare, the understanding and respect for the rules of natural cycles and the management of the technological systems that he or she knows."[30, p. 36]

C. Study Limitations and Future Research

This paper has been informed by reflective practice rather than a systematic literature review or meta-analysis to inform our STEAM-lens based critique of Butt and Dimitrijevic's TDR framework. It remains to be seen whether a different approach would lead to widely divergent outcomes or highlight different key points. We are thus aware that this is more of a pilot study than a comprehensive piece of work.

Our next research step is to conduct a survey among STEAM transdisciplinary researchers and practitioners drawn from a wider international context (i.e., beyond our own experience, networks and focus on Canada and Europe). Thus, our next publication will refine and verify an adapted transdisciplinary collaboration framework through a survey of academics and STEAM industry professionals internationally. Furthermore, we wish to engage more systematically with the TDR-STEAM literature, including more non-English sources as we can identify these in our literature searches. Our language skills enable us to read French and German-language texts, and online translating tools allow up to explore other language-based sources. This is an important consideration, given that by focusing on the northern hemisphere and the dominant academic language, we will have missed context-specific nuances and different research mentalities and contexts, and thus not achieved a holistic global perspective on the subject matter.

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