Transdisciplinary - STEAM Design Toolkit: Leveraging the Benefits of Artistic Approaches in Multidisciplinary Collaborations

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Abstract

Complex global challenges such as climate change, technological disruption, and social inequality increasingly require collaboration across disciplinary boundaries. While STEAM (Science, Technology, Engineering, Arts, and Mathematics) initiatives promise richer perspectives and innovative solutions, assembling and sustaining transdisciplinary design teams that successfully integrate diverse epistemologies remains difficult. Disciplinary co-presence alone does not guarantee integration; carefully designed epistemic and relational conditions are required.

This dissertation addresses this challenge through a seven-year longitudinal action research study conducted in higher education design courses. It argues that art and artistic practices, when authentically integrated with other disciplines, enhance the transformative capacity of transdisciplinary STEAM collaborations. Across seven iterative Plan–Act–Observe–Reflect cycles, the research developed and refined the Transdisciplinary *STEAM Design Toolkit (TD-SDT)* —a framework conceived not as a prescriptive method but as an epistemic infrastructure designed to enable transdisciplinary knowledge creation.

Empirical analysis revealed that effective transdisciplinary collaboration depends on three interacting conditions: *epistemic conditions* which encourage reflexive examination of disciplinary assumptions, *relational conditions* which sustain trust and enable productive friction, and *pedagogical conditions* which scaffold collaborative inquiry through structured design processes. Within such environments, integration occurs through mechanisms of *epistemic crossing*, a process through which participants move beyond disciplinary perspectives to construct shared conceptual spaces. Key *epistemic mediators* include abstraction, narrative reframing, boundary objects, artistic inquiry, and symbolic infrastructures.

Methodologically, the study introduces the *TD Process Assessment Framework*, a structured yet complexity-sensitive approach for evaluating both collaborative process quality and integration depth. The framework combines quantitative assessment of transdisciplinary dimensions with qualitative triangulation across artifacts, reflections, and observational data.

Theoretically, the TD-SDT operationalises a *Constructivism–Systems Thinking–Complexity (CSC) framework* and extends reflexivity-based models of collaboration toward the concept of *epistemic innovation,* describing how new integrative understandings emerge through sustained epistemic crossing. The findings also reposition the arts as *epistemic infrastructure* within STEAM collaboration, demonstrating their role in sustaining ambiguity, activating productive friction, and enabling epistemic movement across disciplinary boundaries.

Together, these contributions advance a coherent model for cultivating transdisciplinary collaboration in complex design contexts and provide educators, researchers, and practitioners with both conceptual guidance and an assessable infrastructure for supporting integrative knowledge creation.

Keywords: transdisciplinarity, STEAM education, transdisciplinarity collaboration, knowledge integration, boundary objects, design-based action research, arts integration, transdisciplinary collaboration, epistemic crossing, arts in STEAM, collaborative design

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List of Acronyms

Acronyms	Definitions
CoP	Community of Practice
CSC Framework	Constructivism–Systems–Complexity Framework
HE	Higher Education
STEAM	Science, Technology, Art, Engineering, Math
STEM	Science, Technology, Engineering, Math
TCS	Henriksen's 7 Transdisciplinary Cognitive Skills
TD	Transdisciplinary
TD-SDT	Transdisciplinary-STEAM Design Toolkit

Note on Language

This thesis generally follows Canadian spelling conventions. However, the term *artifact* is used consistently rather than *artefact*, reflecting its widespread use in science and technology studies and design research literature.

Statement of originality

I hereby certify that all the work described within this thesis is the original work of the author. Any published (or unpublished) ideas and/or techniques from the work of others are fully acknowledged in accordance with the standard referencing practices.

Chantal Rodier

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Chapter 1 Introduction

1.1 Introduction

As the scale, speed, and interconnectivity of global challenges intensify—from climate destabilisation and public health crises to social fragmentation and digital transformation—disciplinary silos increasingly prove inadequate for addressing complex societal challenges, whose interdependent, uncertain, and value-laden nature exceeds the epistemic capacity of any single discipline (Hirsch Hadorn et al. 2008; Max-Neef, 2005; Nicolescu, 2002; Pohl & Hirsch Hadorn, 2008). These challenges do not arise from linear causes nor admit singular solutions. They are systemic, adaptive, and dynamic, demanding integrative and collaborative responses capable of operating under uncertainty.

This research emerges from the recognition that addressing such "wicked problems" requires moving beyond multidisciplinary coordination—where disciplines operate in parallel—toward transdisciplinary collaboration, in which knowledge is co-produced across epistemological boundaries with meaningful participation from creative and non-academic actors (Jahn et al., 2012; Thompson Klein, 2004).

At the core of this inquiry lies the proposition that art and artistic practices, when authentically integrated with other disciplines, enhance the transformative capacity of STEAM design collaborations. Rather than functioning as aesthetic support or communicative embellishment, the arts are positioned here as epistemic (ways of knowing) and ontological (ways of being) agents capable of catalysing ethical reflection, emotional engagement, and imaginative reframing (Eisner, 2002a; Eisner & Powell, 2002; Galafassi, Tàbara, et al., 2018b; Maggs, 2024b).

This chapter introduces the research question, scope, and theoretical foundations guiding this seven-year longitudinal action research study. It establishes the need for transdisciplinary design collaboration and lays the groundwork for the development of the Transdisciplinary STEAM Design Toolkit (TD-SDT), a framework designed to position art not as a supplementary component but as a catalyst for transdisciplinary knowledge creation.

1.2 Research Question and Scope

Addressing contemporary challenges requires forms of collaboration that transcend disciplinary boundaries and move toward genuine transdisciplinarity (Cash et al., 2003; Pennington, 2008; Welp et al., 2006). STEAM (Science, Technology, Engineering, Arts, Mathematics) provides one such context and frames this study.

Despite growing calls for STEAM and interdisciplinary approaches, scholarship remains limited in explaining how such initiatives can be effectively organised. Collaborations are often managed using conventional project structures that insufficiently address epistemological, cultural, and methodological frictions arising when diverse disciplines and stakeholders interact. These frictions include differences in values, research traditions, priorities, and definitions of success (Fam & O'Rourke, 2021).

Although literature increasingly acknowledges the value of integrating arts within STEAM collaborations (Burns et al., 2021; Carter et al., 2021; Rodier & Carter, 2023; Ussher et al., 2023), less attention has been paid to the practical conditions that enable meaningful transdisciplinary collaboration—particularly when the arts function as contributors to knowledge production rather than peripheral enhancements (Rodier & Carter, 2023). Consequently, practice-informed frameworks supporting boundary navigation, trust cultivation, and productive disciplinary tension remain limited (Burns et al., 2021; Carter et al., 2021; Guyotte et al., 2014b; Rodier & Carter, 2023).

This thesis extends existing conceptual boundaries by developing the Transdisciplinary STEAM Design Toolkit (TD-SDT), an original framework consisting of concepts and tools designed to make transdisciplinary STEAM collaborations actionable while positioning art as a core catalyst for knowledge creation. The TD-SDT leverages artistic practices to scaffold transdisciplinary collaboration in higher education.

The guiding research question is:

What toolkit (concepts and tools) can support transdisciplinary knowledge creation within STEAM design collaborations involving art and artists in higher education contexts?

This study adopted an exploratory design-based action research approach. Across seven action research cycles conducted in classroom contexts at the University of Ottawa, the TD-SDT was iteratively developed and refined. Students from diverse disciplinary backgrounds--visual arts, music, theatre, engineering, humanities, and sciences--collaborated on real-world challenges, while student project reports, reflections, and produced artifacts served as units of observation informing analysis of collaboration and knowledge creation processes.

Although this dissertation frequently discusses epistemic integration as a desirable outcome of transdisciplinary collaboration, it does not preclude other valid forms of outcomes such as negotiated plurality, expanded coexistence, productive incompleteness, to name a few.

The study focused on elements enabling and sustaining transdisciplinary collaboration rather than on logistical project management, which is well addressed elsewhere. Although TD-SDT is designed for broader applicability, validation beyond higher education contexts remains future work. Institutional and authorship challenges are acknowledged but fall outside this study's scope.

1.3 Making a Case for Transdisciplinary Design Collaborations

To address the research question and define the collaborative processes and key elements involved in TD knowledge creation, this study constructed a theoretical framework integrating *Constructivism, Systems Thinking, and Complexity Theory*, referred to as the *Theoretical Constructivism–Systems–Complexity (CSC) Framework* or *CSC Framework*.

Together, these lenses explain why knowledge integration becomes essential when confronting real-world complexity.

1.3.1 Constructivism: Knowledge as Situated and Co-Constructed

Constructivism views knowledge as socially produced rather than as a neutral reflection of reality. Kuhn (1963) demonstrated how disciplinary paradigms shape what counts as legitimate questions and methods. Each discipline constructs problems in specific ways, generating what Repko and Szostak (2020) describe as *epistemic silos*. These silos produce distinct ontologies (what exists), epistemologies (how we know), and methodologies (how we investigate), often leading to incommensurable vocabularies and research agendas.

For example, climate change may be framed through atmospheric modeling, governance mechanisms, or community perceptions depending on disciplinary perspective. Without recognising these constructed framings, critical dimensions risk being overlooked (Barry et al., 2008).

Transdisciplinary inquiry responds by reconfiguring how knowledge is co-produced among researchers, stakeholders, and communities (McGregor & Donnelly, 2014). This approach aligns with Vygotsky's (2004) view of socially mediated cognition, in which meaning emerges through interaction rather than isolated reasoning.

1.3.2 Systems Thinking: Interdependence and Feedback

Systems thinking shifts analysis from isolated components to interdependencies, feedback loops, and whole-system behaviour (Meadows, 2008). For example, urban heat island mitigation, requires simultaneous consideration of land use, transportation, energy infrastructures, public health, and social equity as an interconnected web (Davoudi et al., 2012; Meerow et al., 2016).

Systems thinking also foregrounds *leverage points*—strategic interventions capable of generating disproportionate systemic change (Meadows, 2015). Identifying such leverage points requires integrating diverse disciplinary perspectives and modeling dynamic interactions across systems (Sterman, 2006).

1.3.3 Complexity Theory: Emergence, Non-Linearity, and Adaptation

While constructivism and systems thinking establish epistemological and relational foundations, complexity theory explains why wicked problems resist prediction and control. Complexity theorists examine how adaptive, self-organising, and emergent behaviours arise from interactions among heterogeneous agents (Cilliers, 1998; Mitchell, 2009; Mitleton-Kelly, 2003).

Several key concepts are central: *Emergence*: System-level patterns arise from local interactions and cannot be predicted through linear aggregation (Mitchell, 2009) ; *Non-linearity*: Small changes in initial conditions can produce disproportionately large effects (Lorenz, 2017); *Adaptation and Co-evolution*: Agents adjust behaviour in response to feedback, reshaping system structure over time (Holland, 2011); *Networked Interactions*: The topology of social and material networks influences diffusion, amplification, and systemic behaviour (Newman, 2010).

The COVID-19 pandemic illustrated these dynamics. Viral spread and human responses co-evolved across global mobility networks, producing nonlinear escalation patterns (Chang et al., 2021; Chinazzi et al., 2020). Epidemiological models alone proved insufficient; effective responses required integrating epidemiology, behavioural science, policy analysis, data science, and communication (Bhardwaj, 2020; Donnarumma & Pezzulo, 2021; Pezzulo et al., 2020).

Complexity theory suggests that top-down, linear solutions often fail in the presence of emergent and adaptive phenomena (Cilliers, 2000). Instead, adaptive and iterative co-creation processes—hallmarks of transdisciplinary collaboration—become necessary. For instance, drought-resistant crops must be integrated with local farmer knowledge, supply-chain logistics, policy incentives, and climate forecasting to generate resilient food systems. Resilience emerges through coordinated co-evolution rather than isolated innovation.

1.3.4 Synthesising the Three Lenses: Why Inter and Transdisciplinary Methods Are Imperative

Viewed together, constructivism, systems thinking, and complexity theory converge in demonstrating that addressing wicked problems requires epistemic integration rather than isolated inquiry. Disciplines construct distinct framings (constructivism), operate within interacting subsystems (systems thinking), and generate emergent outcomes under uncertainty (complexity). Transdisciplinary collaboration thus becomes not optional but structurally necessary.

From a *constructivist perspective*, disciplines construct their own problem definitions, data priorities, and normative assumptions. To co-construct more comprehensive framings, researchers must engage in epistemic reflexivity—recognising how disciplinary training shapes what is seen and what remains invisible (Barry et al., 2008; Repko & Szostak, 2020). Chapter 2 examines epistemic reflexivity in greater depth.

From a *systems thinking perspective*, complex challenges involve interacting ecological, social, economic, and technological subsystems. Identifying feedback loops and emergent properties requires bridging disciplinary vocabularies—for example, coupling epidemiological models with transportation network analysis or integrating urban planning with hydrological science to address flood risk (Scharmer & Kaufer, 2013; Sterman, 2001).

From a *complexity perspective*, wicked problems are emergent and non-linear; no single discipline can anticipate tipping points or design interventions robust to continuous adaptation (Cilliers, 2000; Mitleton-Kelly, 2003). Tools such as agent-based modeling and participatory simulations combine insights from computer science, behavioural science, and domain expertise to explore possible trajectories (Bonabeau, 2002; Conte & Paolucci, 2014).

Together, these perspectives foreground the need for iterative, adaptive research processes in which knowledge circulates bidirectionally among disciplines, practitioners, and stakeholders (Gibbons et al., 1994; Nowotny et al., 2001). Multidisciplinary collaboration may be necessary, but it is not sufficient. Transdisciplinary collaboration—explicitly grounded in pluralism, reflexivity, and knowledge co-creation—offers a more robust response to contemporary wicked problems (Klein, 2010b; Max-Neef, 2005; Nicolescu, 2010).

1.3.5 Conclusion: Theoretical Imperatives for TD Knowledge Integration

This section has presented the Theoretical CSC Framework, constructed through the integration of Constructivism, Systems Thinking, and Complexity Theory (see Table 1).

The convergence of these three lenses enables a clearer articulation of the collaborative processes and key elements involved in TD knowledge creation. Together, they frame TD collaboration not as a predictable linear process, but as a complex adaptive system that makes space for uncertainty, iteration, and innovation. They also characterise TD knowledge creation as dynamic, emergent, contextual, relational, and co-constructed across domains of expertise and lived experience. Central to this process are pluralism, reflexivity, epistemological integration, and co-creation.

The CSC framework establishes that transdisciplinary collaboration must be reflexive, systemic, and adaptive to respond to real-world complexity. Knowledge is co-constructed across perspectives (constructivism), embedded within interdependent systems (systems thinking), and emergent under conditions of uncertainty (complexity theory).

Yet this theoretical imperative raises a further question: what capacities enable such collaboration to function in practice? Section 1.4 argues that artistic practices provide precisely those capacities.

Table 1 Theoretical CSC Framework (contribution)

Theoretical CSC Framework Ontological, Epistemological, and Methodological Implications for TD Collaboration			
Dimension	**Constructivism**	**Systems Thinking**	**Complexity Theory**
Ontological Assumption	Reality is socially constructed through language, culture, and shared experience.	Reality consists of interdependent subsystems embedded within larger wholes.	Reality is dynamic, nonlinear, and emergent through adaptive interactions.
Epistemological Orientation	Knowledge is co-constructed through dialogue, interpretation, and perspective-taking.	Knowledge emerges from understanding relationships, feedback loops, and systemic structures.	Knowledge is provisional and must account for uncertainty, emergence, and adaptation.
Methodological Implications	Emphasises reflexivity, dialogue, boundary negotiation, and shared meaning-making.	Emphasises system mapping, identification of leverage points, and modeling of interactions.	Emphasises iterative experimentation, adaptive design, and simulation-based inquiry.
Core Concepts	Paradigms; epistemic reflexivity; discourse; cultural mediation.	Feedback loops; system boundaries; leverage points; systemic interdependence.	Nonlinearity; emergence; co-evolution; adaptive capacity; network effects.
Representative Authors	Piaget; Dewey; Vygotsky; Kuhn	Meadows; Capra & Luisi; Sterman	Cilliers; Mitchell; Mitleton-Kelly; Holland
Implications for TD Collaboration	Requires reflexive dialogue across disciplinary framings.	Requires integration across interacting subsystems.	Requires adaptive, iterative collaboration under uncertainty.
Implications for TD Knowledge Creation	Knowledge is relational, contextual, and co-constructed across actors.	Knowledge integrates systemic interdependencies and cross-scale dynamics.	Knowledge emerges through experimentation, feedback, and co-evolutionary learning.

1.4 Making a Case to Include Art in Transdisciplinary Collaborations

In this dissertation, the term *arts* refers specifically to practices associated with the creative or fine arts, including visual arts, sculpture, installation, and related forms of artistic inquiry. These practices are understood not merely as aesthetic contributions but as distinct modes of perception, representation, and meaning making (Dewey, 1934; Eisner, 2002a) that can actively participate in knowledge creation.

If the CSC framework clarifies why transdisciplinary collaboration is necessary, the question becomes what enables it to succeed. From a constructivist perspective, excluding the arts narrows epistemic diversity; from a systems perspective, it limits perceptual range; and from a complexity perspective, it constrains adaptive capacity. Including artistic practices is therefore not a cultural preference but a structural response to the demands identified in Section 1.3.

Artistic practices expand epistemic boundaries. As epistemic and ontological agents, the arts reshape how we know and what becomes perceptible. They cultivate ontological pluralism, enabling multiple ways of being and knowing (Eisner, 2002b; Galafassi, Tàbara, et al., 2018b). By surfacing hidden assumptions and enabling imaginative reframing, art transforms the conditions under which collaboration unfolds.

The arts also support ethical reflection, interrogating the moral dimensions of scientific advances (Kac, 2005; Zylinska, 2009a). Ambiguity tolerance is cultivated, strengthening teams' capacity to remain adaptive under uncertainty (Davis & Sumara, 2006). The arts generate transdisciplinary knowledge by integrating emotion, aesthetics, and embodiment into inquiry (L. Candy & Edmonds, 2018).

From there, the arts shape shared futures: speculative artistic practices help communities imagine alternatives (Le Guin, 1985; Nurmis, 2016). Artists contribute to symbolic infrastructure—cultural scaffolding that influences behaviour (Olafur Eliasson, 2003; Vervaeke, 2019).

Together, these contributions demonstrate that the arts are structural conditions for transdisciplinary collaboration. Where disciplines construct realities, art expands them; where systems interdepend, art reveals their dynamics; and where complexity emerges, art cultivates adaptive capacity.

The arts' contributions can be organised functionally into three progressive layers of contributions: Foundational Contributions, Epistemic & Ontological Contributions and Systemic Contributions.

1.4.1 Foundational Contributions

1.4.1.1 Creative Problem Solving

Artists contribute non-linear and associative modes of thinking that enable problems to be approached from unexpected angles (Ambrose, 2015; Eisner, 2002a; Rolling, 2016a). Through metaphorical reasoning, aesthetic experimentation, and boundary-crossing inquiry, artistic practices enrich innovation processes in domains such as design, sustainability, and technology (Candy et al., 2021; Cross, 2011).

For example, collaborations at the MIT Media Lab involving dancers and musicians contributed to the development of expressive wearable technologies, reframing design challenges around human emotion and embodied movement (Moss, 2011). Such cases illustrate how artistic methodologies can disrupt conventional problem framings and generate novel technical solutions. Artistic practices thus expand the cognitive repertoire available to transdisciplinary teams.

1.4.1.2 Humanising Complex Issues

The arts translate scientific and technological concepts into emotionally resonant and culturally situated forms (Glass & Wilson, 2016; Rolling, 2016b). Through visual art, music, performance, and storytelling, abstract or technical content becomes accessible and meaningful to broader publics.

Projects such as *Cape Farewell*, which brought artists and scientists together on Arctic expeditions, demonstrate how artistic production can render climate science affectively compelling. In contexts such as climate change and public health, fostering empathy is often essential for motivating behavioural change (Galafassi, 2018; Galafassi, Daw, et al., 2018; Galafassi, Tàbara, et al., 2018; Nurmis, 2016; Roosen et al., 2018).

In transdisciplinary collaborations, art functions as an interpretive medium that enables communities to perceive, feel, and critically engage with complex systemic dynamics.

1.4.1.3 *Fostering Emotional and Psychological Resilience*

Transdisciplinary collaboration frequently unfolds under conditions of uncertainty, ambiguity, and urgency. Artistic practices can create spaces for expression and emotional processing, thereby supporting psychological resilience within collaborative environments (Camic & Chatterjee, 2013; Chatterjee & Camic, 2015; Lemon, 2022; Stuckey & Nobel, 2010).

Through improvisation, metaphor, narrative, and embodiment, artistic engagement can help teams navigate emotional impasses and sustain motivation. For example, participatory theatre and visual storytelling have been used to support community engagement with difficult sustainability transitions, enabling participants to explore complex futures in constructive ways (Galafassi, 2018; Galafassi, Daw, et al., 2018; Galafassi, Tàbara, et al., 2018).

By structuring opportunities for affective engagement, the arts help sustain the psychological and relational conditions necessary for collaboration on complex societal issues.

1.4.2 Epistemic & Ontological Contributions

1.4.2.1 *Functioning as Epistemic and Ontological Agents*

The arts operate not only as modes of representation but as active agents shaping how we understand (epistemology) and inhabit (ontology) the world. They cultivate ontological pluralism by affirming multiple modes of being, sensing, and relating. Artistic practices catalyse emotional engagement, ethical reflection, and imaginative reframing, thereby legitimising alternative epistemologies (Eisner, 2002a; Eisner & Powell, 2002; Maggs, 2024a, 2024b).

In sustainability transformations research, artistic interventions have shifted communities' sense of place and identity through poetic, sensory, and embodied engagement (Galafassi, Tàbara, et al., 2018). Projects such as *Seeds of Good Anthropocene* use visual and narrative art to catalyse sustainability initiatives grounded in hope and shared values (Galafassi, Daw, et al., 2018; Galafassi, Tàbara, et al., 2018a; Maggs, 2024b).

Through such engagements, art reshapes not only what is known, but how knowing occurs and who participates as a knower.

1.4.2.2 Cultivating Tolerance for Ambiguity

Art fosters tolerance for ambiguity and uncertainty—conditions inherent in transdisciplinary collaboration and complex problem-solving. Artistic processes embrace contradiction, fluidity, and emergence rather than forcing premature closure (Davis & Sumara, 2006; Veness, 2010). Through open-ended aesthetic practices, collaborators learn to dwell in the "not-yet-known," cultivating comfort with complexity and indeterminacy.

For example, in participatory design workshops within the *Designing for Transitions* project (Manzini, 2015), participants used abstract sculpture and collage to explore possible futures. These activities foregrounded ambiguity as a creative resource rather than a liability, strengthening participants' cognitive and emotional capacity to remain generative within evolving systems of practice.

1.4.2.3 Deepening Ethical Reflection

In collaborations involving science and technology, the arts provide critical ethical reflection on the implications of new developments. Artistic practices interrogate the ethical dimensions of scientific and technological advances, surfacing unspoken assumptions and moral dilemmas (Kac, 2005; Rodier & Carter, 2023; Wilson, 2002; Zylinska, 2009). Bioartists such as Eduardo Kac challenge boundaries between human and nonhuman, nature and machine—provoking public discourse on biotechnology and ethics.

Artistic provocations can function as "moral laboratories," spaces where the consequences of emerging systems are explored through imagination and affect. In this way, artists interrogate the social and moral dimensions of innovation, helping ensure that technological progress remains responsive to human values and collective wellbeing.

1.4.2.4 Generating Transdisciplinary Knowledge

Artistic methods generate new forms of knowing by integrating emotion, intuition, aesthetics, and embodiment into cognitive inquiry (Eisner, 2002a; Eisner & Powell, 2002; Rolling, 2016a). The arts expand the epistemological range of transdisciplinary work by foregrounding ways of knowing often marginalised within conventional science.

Candy & Edmonds (2018), for example, describe "experiential futures" that use immersive environments, narrative scenarios, and speculative artifacts to create situated, affective encounters with possible futures. Such approaches blend imagination, theory, and design research. Artistic contributions thus enrich traditional methods, supporting integrative and innovative solutions that transcend disciplinary boundaries (L. Candy & Edmonds, 2018; Root-Bernstein, 2015; S. Wilson, 2002).

1.4.3 Systemic Contributions

1.4.3.1 Building Shared Futures

Artists play a crucial role in imagining alternative futures, particularly in sustainability and post-carbon contexts (A. Aumann, 2022). Speculative fiction writers and artists help shape collective imaginaries that galvanise hope and action (Candy & Dunagan, 2017; Demos, 2016; Nurmis, 2016).

Works such as Octavia Butler's *Parable of the Sower*, Ursula K. Le Guin's *The Dispossessed* and *Always Coming Home*, Arthur C. Clarke's *2001: A Space Odyssey*, Jacques Lob's *Le Transperceneige*, and N.K. Jemisin's *Broken Earth* trilogy construct alternative ecological, technological, and social worlds.

These cultural productions function as world-making practices. They open space for dialogue about systemic change and human potential, enabling alternative futures to be envisioned, debated, and pursued. Beyond entertainment, they contribute to collective sense-making during periods of planetary crisis and orient shared trajectories of transformation.

1.4.3.2 Enabling Behavioural Change and Contributing to Symbolic Infrastructure

Artists contribute to behavioural change by addressing the emotional and cultural dimensions of global issues (Aumann C., 2022; Maggs, 2024a; Vervaeke, 2019). Vervaeke (2019) describes this as the construction of "symbolic infrastructure"—cultural scaffolding that carries meaning, identity, and value across contexts and guides behaviour at depth.

Environmental art installations such as Olafur Eliasson's Ice Watch (2014) bring melting glacial ice into urban environments, creating visceral encounters that transform emotional relationships to climate change. Unlike rational argument alone, such interventions activate aesthetic, moral, and existential registers that can motivate action.

As Maggs (2024a) argues, technological, political, and economic infrastructures are necessary but insufficient for transformation. Symbolic infrastructure provides the experiential grounding that enables shifts in subjectivity and collective practice.

1.4.4 Affirmative Ethics Further Supports Art's Transformative Role

Affirmative ethics, articulated by posthumanist thinkers such as (Braidotti, (2013, 2019b, 2019a) , offers a philosophical foundation for integrating the arts into transdisciplinary collaboration. Drawing on Spinoza and Deleuze, affirmative ethics emphasises relationality, immanence, and the generative force of difference within dynamic assemblages. Subjects are understood as processual assemblages shaped through interaction.

Ethics, within this framework, is not rule application but an active process of becoming that fosters mutual flourishing. Central concepts include *potentia*—the capacity to affect and be affected—and *joy* as an ethical orientation toward empowerment and creative transformation.

The arts are not merely morally instructive; they are generative forces capable of producing new subjectivities and relational configurations (A. Aumann, 2022; Vervaeke, 2019). By enabling embodied experience and imaginative reframing, artistic practices align closely with affirmative ethics' commitment to life-affirming transformation.

Within transdisciplinary settings—where socio-ecological complexity challenges reductionist approaches—affirmative ethics reframes difference as creative potential. It invites collaborative practices that make space for new voices, subjectivities, and relational forms.

1.4.5 Synthesis: Why the Arts Are Foundational to Transdisciplinary Collaboration

Across the preceding sections, the literature has shown that the arts contribute to transdisciplinary collaboration in ways that extend beyond communication or creativity alone. Artistic practices support ethical reflection, cultivate tolerance for ambiguity, expand epistemological range, generate shared imaginaries of the future, and operate as epistemic and ontological agents capable of reshaping identity and relationality. They also contribute to behavioural transformation through the construction of symbolic infrastructure and align philosophically with affirmative ethics' emphasis on relational becoming and life-affirming transformation.

Together, these contributions suggest that the arts are not peripheral enhancements to transdisciplinary collaboration but structural conditions that enable it to function productively within complexity. Where constructivism reveals that knowledge is socially constructed and value-laden, the arts expose and reconfigure those constructions. Where systems thinking highlights interdependence and feedback, the arts render invisible dynamics perceptible and experientially meaningful. Where complexity theory foregrounds emergence and uncertainty, the arts cultivate the capacities required to remain adaptive, reflexive, and generative within indeterminacy.

These contributions unfold across three progressively deepening layers of influence. At a foundational level, the arts operate in a creative and humanising capacity aligned with constructivism, supporting situated meaning-making and broadening interpretive frames. At a second layer, artistic practices act as epistemic and ontological catalysts—aligned with constructivism and complexity—both generating new forms of knowledge and destabilising entrenched assumptions. At a third and systemic layer, the arts align with systems thinking and complexity by shaping behaviours, cultural norms, and institutional structures, contributing to longer-term structural transformation. This layered progression clarifies that artistic inclusion functions not as an additive feature, but as a structural driver of transdisciplinary capacity within complex systems.

The literature therefore positions artistic inclusion as both epistemically necessary and ethically grounded. If transdisciplinary collaboration seeks to address wicked problems characterised by uncertainty, pluralism, and systemic interdependence, then the arts provide structural, epistemic, and affective capacities that remain systematically underdeveloped in technoscientific domains. The question that follows is not whether art belongs in transdisciplinary STEAM design, but how its contributions can be intentionally scaffolded, operationalised, and assessed within higher education contexts.

This question motivates the present research.

1.5 Conclusion Chapter 1

Amid converging environmental, health, and social crises, contemporary "wicked" problems exceed the explanatory and practical capacity of single disciplines (Rittel & Webber, 1973; Vandenbroeck, 2012). The CSC framework demonstrates that knowledge capable of addressing such problems must be reflexive, systemic, and adaptive. Transdisciplinary collaboration thus emerges not as an academic preference but as an epistemic necessity.

This chapter has further argued that artistic practices provide capacities essential to this form of collaboration. By expanding epistemic boundaries, rendering systemic interdependencies perceptible, and cultivating tolerance for uncertainty, the arts function as structural, epistemic, and ontological catalysts within transdisciplinary STEAM design.

The research therefore investigates which frameworks and tools can intentionally scaffold these capacities within higher education contexts. In response to conceptual and practical gaps identified in the literature, this thesis develops and examines the Transdisciplinary STEAM Design Toolkit (TD-SDT).

By operationalising the contributions identified in Section 1.4, the TD-SDT seeks to make transdisciplinary collaboration deliberate, scaffolded, and assessable. In doing so, this research positions Transdisciplinary STEAM Design not as an optional enhancement, but as a necessary evolution in education and research—capable of fostering more adaptive, humane, and life-affirming responses to twenty-first-century complexity.

1.6 Thesis Outline

Chapter 2 deepens the theoretical foundations, examining STEAM, distinctions among disciplinary modes, epistemic reflexivity, trust, and productive friction as enabling conditions for transdisciplinarity.

Chapter 3 presents the action research methodology, detailing research design, data collection, and analytic procedures across seven iterations.

Chapters 4 and 5 document the iterative development and refinement of the Transdisciplinary STEAM Design Toolkit (TD-SDT), structured through the Plan–Act–Observe–Reflect cycles of action research.

Chapter 6 synthesises the TD-SDT framework and tools, analysing their epistemic functions and practical applications.

Chapter 7 discusses the study's theoretical, methodological, and pedagogical contributions, addresses implications, limitations, and identifies directions for future research.

1.7 Research Dissemination

During this doctoral research, elements of the work presented in this thesis were disseminated through peer-reviewed publications, conference presentations, and collaborative research initiatives as part of ongoing scholarly knowledge mobilisation. These outputs contributed to refining the research questions, developing the Transdisciplinary STEAM Design Toolkit (TD-SDT), and articulating the TD Process Assessment Framework.

Presenting interim findings to academic and professional communities enabled emerging ideas to be discussed and refined through scholarly dialogue. Conferences and publications also provided opportunities to examine the role of artistic practices in transdisciplinary collaboration and knowledge creation within STEAM education contexts nationally and internationally.

These scholarly outputs document key stages in the project's evolution, including early explorations of STEAM collaboration, the integration of artistic practices in engineering education, and the development of approaches for assessing transdisciplinary teamwork. A list of publications and related outputs produced during this research is provided in APPENDIX B.

In addition, several student projects and collaborative artworks developed through this research were publicly exhibited on campus and at partner institutions, contributing to broader explorations of artistic practices as epistemic infrastructures within transdisciplinary collaboration.

Chapter 2 Conceptual Foundations and Structural Gaps in Transdisciplinary STEAM

2.1 Introduction – Conceptual Foundations

Chapter 1 established the Constructivism–Systems Thinking–Complexity (CSC) framework as the theoretical orientation guiding this study and positioned artistic practices as structural contributors to transdisciplinary collaboration. Building on this foundation, the present chapter examines how transdisciplinary collaboration has been theorised, operationalised, and assessed within existing literature.

Although contemporary scholarship increasingly recognises the importance of integrating diverse forms of expertise, frameworks supporting art-inclusive collaboration remain conceptually fragmented and unevenly operationalised. This chapter therefore maps key developments in transdisciplinary and STEAM discourse, identifies advances and limitations in existing models, and synthesises conceptual mechanisms relevant to collaborative knowledge creation in higher education contexts.

The chapter proceeds in five stages. First, it clarifies distinctions among multidisciplinary, interdisciplinary, and transdisciplinary collaboration. Second, it traces the evolution and critiques of STEAM discourse. Third, it examines frameworks commonly used to structure art-inclusive collaborative practice. Fourth, it reviews approaches to assessing transdisciplinary processes and outcomes. Finally, it synthesises conceptual mechanisms that support collaboration across epistemic boundaries.

Through this synthesis, the chapter identifies structural gaps in current approaches and motivates the development of the *Transdisciplinary STEAM Design Toolkit (TD-SDT)* introduced at the end of the chapter.

2.2 Art-Inclusive Transdisciplinary STEAM Landscape

2.2.1 Transdisciplinary Distinctions

Transdisciplinary collaboration differs from multidisciplinary and interdisciplinary approaches in its emphasis on *epistemic integration rather than disciplinary coordination*. Multidisciplinary work juxtaposes perspectives from different fields, while interdisciplinary work seeks synthesis across existing disciplinary frameworks *(Choi & Pak, 2006; Colucci-Gray et al., 2013; Lawrence & Després, 2004)*. By contrast, transdisciplinary collaboration aims to develop shared conceptual architectures that transcend disciplinary boundaries. This distinction is central to the present study, which examines not only collaboration across fields but also the conditions under which new integrative forms of knowledge emerge.

2.2.2 Terminology Proliferation in Art Inclusive Models

Within art-inclusive contexts, a proliferation of terms—ArtScience, SciArt, SEAD, research-creation, hybrid models, and STEAM—reflects ongoing efforts to bridge artistic and scientific domains (Perignat & Katz-Buonincontro, 2019; Zacharias, 2018) (list of terms in APPENDIX B). However, terminological diversity has not resolved ambiguity regarding the epistemic role of the arts. In many instances, artistic practices are incorporated instrumentally—as vehicles for engagement, communication, or creativity enhancement—rather than as equal contributors to problem framing, methodological design, and evaluative criteria. As a result, the presence of art within collaborative models does not guarantee epistemic integration (Perignat & Katz-Buonincontro, 2019).

2.2.3 Evolution and Critiques of STEAM

The evolution of STEAM reflects ongoing attempts to address perceived limitations of STEM education by reintegrating artistic practices into scientific and technical domains. Since its early articulation in the mid-2000s, STEAM discourse has evolved through several overlapping phases.

Early STEAM advocacy emphasised *access and inclusion*, presenting the arts as a strategy for broadening participation in STEM fields, particularly among groups historically underrepresented in technical disciplines. Creativity and engagement were framed as mechanisms for increasing diversity and motivation (Land, 2013; Maeda, 2013; Segarra et al., 2018; Ge et al., 2015; Kelliher, 2016; Smith, 2015).

A second phase linked STEAM to the cultivation of *"21st-century skills"*, including creativity, collaboration, critical thinking, and innovation. In this framing, artistic practices were often positioned as catalysts for innovation within technological or entrepreneurial contexts (APPENDIX D lists documented STEAM benefits). Although this perspective recognised the cognitive value of artistic practice, the arts were frequently treated as supportive tools rather than epistemic contributors (Ge et al., 2015; K. Guyotte et al., 2014; Kelliher, 2016).

More recent scholarship advances a *transdisciplinary orientation*, suggesting that artistic, scientific, and technical practices can co-constitute inquiry in addressing complex societal challenges (Costantino, 2018; Ghanbari, 2015; Guyotte, 2020; Peppler & Wohlwend, 2018). Despite this rhetorical shift toward integration, operational frameworks capable of sustaining art-inclusive transdisciplinary collaboration remain underdeveloped (Perignat & Katz-Buonincontro, 2019).

2.2.4 STEAM Inc as Structural Reference Point

In higher education contexts, the STEAM Inc collective articulated seven core principles for STEAM practice, emphasising equal footing between arts and sciences, openness to uncertainty, collaboration, prototyping, and multimodal inquiry (Carter et al., 2021). These principles provide an important normative orientation for art-inclusive STEAM environments.

Building on this foundation, the STEAM Inc initiative further proposed a fourfold classification of STEAM approaches—Behaviour, Cultures, Engagement, and Space—intended to characterise how STEAM projects are structured within educational contexts (Burns et al., 2021). This typology advances conceptual clarity by distinguishing pedagogical orientations and institutional configurations.

More recently, the project introduced an evaluation framework designed to assess eight competencies—including collaboration, communication, exploration, critical thinking, civic engagement, sustainability, metacognition, and wellbeing—primarily through participant surveys (Ussher et al., 2023). This represents a significant step toward formalised assessment of STEAM processes.

These initiatives demonstrate an increasing effort to articulate principles, categorise approaches, and evaluate outcomes within higher-education STEAM practice. However, while they clarify cultural orientation and participant competencies, they do not specify mechanisms for managing epistemic difference, tracing integration depth within collaborative artifacts, or assessing the emergence of transdisciplinary knowledge creation over time. The need remains for a framework capable of linking relational dynamics, epistemic mediation, and artifact-level integration within a coherent design-and-assessment architecture.

2.2.5 Synthesis - Fragmentation of Art-Inclusive STEAM

Collectively, the definitional landscape, terminological proliferation, evolving rationales, and higher-education principles reveal a common pattern: while interest in art-inclusive transdisciplinarity is growing, conceptual clarity and operational coherence remain fragmented. This fragmentation motivates the need for a structured framework capable of intentionally scaffolding and evaluating transdisciplinary STEAM collaboration—the kind of integrated design-and-assessment architecture developed in this thesis as the Transdisciplinary STEAM Design Toolkit (TD-SDT).

2.3 Collaborative Frameworks Used in STEAM Education - Failing to Integrate Art

Although STEAM literature increasingly recognises the potential value of integrating the arts into STEM contexts, it offers limited guidance on the conditions and practices required for sustained collaboration in which the arts function as epistemic contributors rather than adjunct elements (Rodier & Carter, 2023). As a result, there remains a relative scarcity of robust frameworks and practical tools that explicitly support cross-epistemic negotiation, trust cultivation, and the management of productive tensions through which transdisciplinary knowledge may emerge.

This section reviews three prominent approaches referenced in the literature for structuring STEAM collaboration processes: Design Thinking, the Double Diamond model, and the Creative Enquiry Process model. Each provides useful process scaffolding, yet each also exhibits limitations in addressing the epistemic and relational challenges posed by multi-disciplinary teams seeking transdisciplinary knowledge creation.

2.3.1 Design Thinking

Design thinking is commonly described as a set of cognitive processes and practices used by designers to engage complex problems (Henriksen et al., 2019; Watson & Watson, 2013). Multiple variants exist across contexts. One widely cited model—associated with the Stanford d.school—organises design work into five modes: empathise, define, ideate, prototype, and test (Henriksen et al., 2019). Design thinking has become particularly prevalent in STEM and STEAM settings; however, the literature shows wide variation in how the arts are conceptualised and integrated within its application. In some instances, the arts are treated as synonymous with general creativity or making; in others, artistic methods are minimally specified or absent, limiting guidance for sustained arts integration across project phases (Perignat & Katz-Buonincontro, 2019).

2.3.1.1 Prototyping

Prototyping is a central practice within *Design Thinking*, serving as a bridge between abstract ideas and tangible experience. Rooted in constructivist and experiential learning theories (Kolb, 2014; Schon, 1983), it enables designers to externalise thoughts, test assumptions, and engage with complexity through iterative cycles of making and reflection. Rather than aiming for perfection, prototypes act as thinking tools—material embodiments of hypotheses that invite exploration, dialogue, and feedback (T. Brown, 2019; Kelley & Kelley, 2013). In this sense, *prototyping* transforms uncertainty into a generative condition, allowing multidisciplinary teams to confront *ambiguity*, reveal hidden constraints, and co-construct shared understanding through concrete interaction.

Within transdisciplinary and STEAM contexts, prototyping also functions as a boundary object (Star & Griesemer, 1989) that facilitates collaboration across epistemic divides. By giving form to emerging ideas, prototypes allow participants from diverse backgrounds—engineers, artists, scientists, and community members—to engage in a shared process of meaning-making and sense-testing. This tangible mode of inquiry supports both cognitive and affective engagement, enabling stakeholders to see and feel possibilities rather than merely discuss them.

Ultimately, prototyping is not only a tool for innovation but also a reflective practice that integrates knowledge across disciplines, fostering creativity, adaptability, and mutual understanding—the very conditions necessary for transdisciplinary knowledge creation.

2.3.1.2 Conclusion for Design Thinking

In the STEAM literature, design thinking is frequently invoked as a generic process scaffold, but it is often under-specified with respect to the role of the arts and the conditions required for cross-disciplinary integration. As Perignat & Katz-Buonincontro's (2019) note, the "A" in STEAM is interpreted inconsistently—variously referring to arts education, non-STEM disciplines, or broad pedagogies such as project-based learning or making. This ambiguity limits the capacity of design thinking, as typically presented in STEAM discourse, to provide consistent guidance for integrating artistic epistemologies as distinct contributors within collaborative knowledge creation.

2.3.2 Double Diamond Model

The Double Diamond model, developed by the UK Design Council (2005), structures design work into four phases—Discover, Define, Develop, and Deliver—organised through two cycles of divergence and convergence. The first cycle supports problem exploration and framing (Discover → Define), while the second supports solution development and refinement (Develop → Deliver). The model offers a clear visualisation of iteration and ambiguity within design processes, reinforcing the importance of problem framing prior to solution selection (Design Council, 2005). In collaborative contexts, the model can support delayed closure and sustain exploration across multiple perspectives, particularly during early-stage sensemaking.

The *Double Diamond model* complements *Design Thinking* by visually mapping its iterative and divergent–convergent nature across four key phases: *Discover, Define, Develop*, and *Deliver* (Design Council, 2005). In engineering courses at uOttawa, the Double Diamond model is presented as an approach to execute the iterative phase of *Design Thinking*. Both *Double Diamond* and *Design Thinking* frameworks emphasise understanding problems deeply before generating and refining solutions.

In transdisciplinary collaboration, the *Double Diamond* helps participants resist the temptation to jump prematurely to solutions, instead encouraging them to slow down, explore multiple perspectives, and embrace ambiguity in the early phases (T. Brown, 2019; Dorst, 2019).

The arts often exemplify this approach through iterative cycles of exploration, experimentation, and refinement. For example, in participatory art projects, artists and communities may begin with divergent idea generation—surfacing many possible interpretations of a shared issue—before converging on an expression or artifact that embodies collective meaning. Within educational contexts, the Double Diamond provides a scaffold that makes the nonlinear and emergent aspects of creativity more accessible, allowing students to see uncertainty not as failure but as a productive stage in the process.

By cycling between expansion and focus, participants develop the tolerance for ambiguity and reflective patience that complexity theory suggests is necessary for navigating “wicked” problems (Rittel & Webber, 1973; Snowden & Boone, 2007). In this way, the Double Diamond is less a rigid method than a guiding framework that legitimises uncertainty and iteration as vital parts of collaborative knowledge creation.

2.3.3 Creative Enquiry Process Model

Costantino (2018)proposes an iterative Creative Enquiry Process model to support arts integration with STEM. The model foregrounds studio-based learning practices commonly associated with art and design education—critical making, object-based learning, critique, and exhibition/presentation—and organises them into a cyclical process of inquiry, iteration, feedback, and refinement. Costantino also draws on Root-Bernstein & Root-Bernstein’s (2001)“Thirteen Thinking Tools” as a conceptual and curricular organising structure to support creative development.

The Creative Enquiry Process model is notable for positioning art pedagogies as central rather than peripheral. However, as a process framework it provides less explicit guidance for managing the relational and epistemic dynamics that arise within multi-disciplinary teams, such as trust-building, role negotiation, epistemic reflexivity, and the productive handling of cross-disciplinary tension.

2.4 Structural Limitations of Existing Frameworks

Across the reviewed literature, a recurring critique concerns the limitations of widely used frameworks in STEAM and engineering design—Design Thinking (DT), the Double Diamond model (DD), and the Creative Enquiry Process (CEP) model. Although these frameworks provide useful structure for iterative development and innovation, they tend to under-specify the epistemic and relational conditions required for transdisciplinary (TD) knowledge creation. A central limitation is the frequent treatment of the arts as instrumental supports—enhancing creativity, engagement, or communication—rather than as epistemic partners contributing distinct cognitive, affective, and philosophical capacities to inquiry. As a result, these frameworks more reliably support multidisciplinary coordination than sustained transdisciplinary transformation.

Design Thinking and Double Diamond models offer flexible scaffolds for divergent–convergent cycles and commonly used tools such as empathy mapping and prototyping. However, they provide limited guidance for integrating artistic epistemologies across a full project lifecycle. The Creative Enquiry Process model advances arts integration by embedding studio pedagogies—critical making, critique, and exhibition—yet it does not fully address the relational and epistemological tensions that accompany cross-disciplinary collaboration. More broadly, the frameworks reviewed do not systematically account for collaborative preconditions frequently identified as necessary for TD work, including psychological safety, trust, equitable participation, and the capacity to hold productive friction. In the absence of such scaffolding, teams may revert to disciplinary defaults, and artistic contributions risk being reduced to symbolic or tokenistic roles. Table 2 Comparative Table: Limitations of Existing STEAM Frameworks summarises these differences.

Table 2 Comparative Table: Limitations of Existing STEAM Frameworks

Framework	Strengths Supporting STEAM	Critical Shortcomings for TD Collaboration	Resulting Limitation
Design Thinking (DT)	Human-centred, iterative; supports empathy mapping and prototyping as boundary objects; accessible to engineering students	"Arts" not explicitly defined as epistemic; lacks structures for trust-building, friction management, or deep artistic integration	Risk of superficial arts add-on; remains multidisciplinary
Double Diamond (DD)	Makes ambiguity and iteration visible; validates divergent/convergent cycles	Inherits DT's shortcomings; no mechanisms for relational conditions or philosophical depth	Cannot support long-term epistemic transformation
Creative Enquiry Process (CEP)	Integrates art pedagogies (critique, exhibition, critical making, object-based learning)	Focuses on process but lacks full-team relational structures, trust scaffolding, and epistemic reflexivity	Improves arts integration but remains insufficient for reliable TD outcomes
****All Existing Frameworks (Synthesis)**	Offer organisational and creativity-supporting structures	Fail to address foundational human needs (trust, safety), cross-epistemic negotiation, and symbolic/ontological integration	Cannot consistently generate transdisciplinary knowledge creation

These limitations indicate that successful transdisciplinary collaboration depends not only on design processes but also on relational and epistemic mechanisms that enable participants to negotiate disciplinary difference.

2.5 Conceptual Mechanisms Enabling TD Collaboration

This section builds on the limitations identified in existing STEAM and design-oriented frameworks. Across transdisciplinary research, design studies, science and technology studies (STS), and art–science collaboration literature, several mechanisms are identified as mechanisms capable of coordinating action, productive collaboration across epistemic boundaries. These mechanisms include mediating artifacts, epistemic reflexivity, productive friction, trust and psychological safety, mutual learning, ambiguity tolerance, and aesthetic modes of inquiry.

For analytical clarity, the discussion distinguishes between mechanisms that mediate collaboration across epistemic boundaries and the relational and epistemic conditions that sustain such collaboration over time. Although widely discussed, these mechanisms are seldom integrated within a coherent pedagogical architecture capable of intentionally scaffolding transdisciplinary collaboration in higher-education STEAM contexts.

Transdisciplinary collaboration does not arise automatically from disciplinary diversity. Rather, it requires mediating mechanisms capable of coordinating action, restructuring conceptual frames, and sustaining shared meaning across epistemic difference (Klein, 2010a; Pohl & Hirsch Hadorn, 2007). Because disciplines differ in language, methods, representational practices, and evaluative standards, collaboration depends not only on dialogue but also on material, conceptual, and symbolic mediators that render difference negotiable and productive (Star & Griesemer, 1989).

The following sections synthesise insights from STS, educational research, creativity studies, and artistic practice to clarify how collaboration across epistemic boundaries can be coordinated, reframed, and sustained. While each body of literature offers partial insights, their integration into a coherent pedagogical and evaluative architecture remains underdeveloped—an important gap addressed by this research.

2.5.1 Mediation Across Epistemic Boundaries

Research across science and technology studies (STS), design studies, arts, and transdisciplinary research highlight several mechanisms that appear to support collaboration across epistemic boundaries. These mechanisms help actors coordinate work, communicate across disciplinary languages, reframe conceptual problems, and embed emerging insights within shared cultural meanings.

Four mechanisms are particularly relevant: *boundary objects*, which enable coordination through shared artifacts interpreted across disciplines (Star & Griesemer, 1989); *interactional expertise*, which supports meaningful dialogue between disciplinary communities (Collins, 2004); *transformational creativity*, which enables conceptual reframing and the expansion of problem spaces (Boden, 2004; Dorst, 2015); and *symbolic infrastructure*, which shapes shared narratives, values, and cultural orientations (Maggs, 2024a; Vervaeke, 2019).

These mechanisms are discussed across multiple literatures concerned with collaboration, creativity, and knowledge integration. While each provides valuable insight into how epistemic differences can be negotiated, they are rarely examined together within a coherent pedagogical architecture for transdisciplinary collaboration.

2.5.1.1 Boundary Objects

The concept of boundary objects was introduced by Star & Griesemer (1989) in their study of interdisciplinary collaboration at the Berkeley Museum of Vertebrate Zoology. Boundary objects are artifacts—material or conceptual—that are sufficiently flexible to be interpreted differently by participants from distinct social worlds while remaining robust enough to maintain a shared identity across those interpretations.

Boundary objects enable collaboration without requiring full consensus on meaning or shared epistemological commitments. They are characterised by interpretive flexibility, cross-context usability, and a combination of standardisation and local adaptability (Bowker & Star, 1999).

Central to boundary-object theory are the notions of *coordination* and *stabilisation*. *Coordination* refers to the establishment of sufficient interpretive alignment to enable joint action across epistemic communities without requiring conceptual convergence (Carlile, 2002). *Stabilisation* refers to the provisional structuring of interaction through shared artifacts that provide durable reference points across time.

Boundary objects therefore stabilise collaboration by externalising ideas into shared representations that accommodate multiple interpretations while maintaining functional coherence. In transdisciplinary design contexts, prototypes, models, diagrams, and installations frequently serve this role by rendering disciplinary assumptions visible and negotiable (Carlile, 2002; Star & Griesemer, 1989).

From the perspective of the Constructivism–Systems–Complexity (CSC) framework introduced earlier, boundary objects function as relational stabilisers within complex adaptive collaborations: they provide provisional structure that enables co-construction under conditions of uncertainty without imposing epistemic uniformity.

However, while boundary objects support coordination across epistemic difference, they do not necessarily transform the conceptual structures participants bring to collaboration. Other processes discussed in the creativity and design literature address how conceptual reframing and the expansion of problem spaces may occur.

2.5.1.2 Interactional Expertise

Within STS, Collins (2004) introduced the concept of *interactional expertise* to describe the ability to master the language and conceptual distinctions of a specialist domain without possessing its full practical competence. Distinct from contributory expertise (Collins & Evans, 2007; Collins & Evans, 2002), interactional expertise enables meaningful dialogue across disciplinary communities through discursive immersion.

Interactional expertise therefore explains how individuals may communicate across domains without complete retraining in another discipline. However, the concept focuses primarily on communicative competence at the level of individual actors and offers limited guidance regarding how collaborative environments might be intentionally structured to support deeper negotiation of assumptions and evaluative standards.

Interactional expertise thus complements boundary-object theory. Whereas boundary objects stabilise coordination through shared artifacts, interactional expertise supports dialogue by enabling participants to engage meaningfully with one another's conceptual vocabularies and disciplinary distinctions.

2.5.1.3 Transformational Creativity

Whereas boundary objects primarily support coordination across existing epistemic positions, creativity research highlights processes that operate at the level of conceptual restructuring. Drawing on Boden's (2004) framework, transformational creativity occurs when the generative rules of a conceptual domain are altered, thereby expanding the space of possible solutions rather than merely combining existing elements.

Such transformations often emerge through processes including analogical transfer (Gentner, 1983), conceptual blending (Fauconnier & Turner, 2008), and frame innovation (Dorst, 2015). These processes enable lateral movement across epistemic boundaries and support reframing of the problem space.

In complex collaborative systems, such reframing can function as *cognitive attractors*—shared abstractions that circulate across domains while gradually reshaping how problems are understood Schon, 1983; Sperber, 1996).

In STEAM contexts, transformational creativity often emerges through artistic abstraction, metaphor-driven inquiry, and speculative design practices. These approaches enable participants to move beyond disciplinary logics—not by prematurely harmonising them, but by reconfiguring the assumptions that structure them.

2.5.1.4 Symbolic Infrastructure

In contrast to mechanisms that support coordination or conceptual reframing, some scholars argue that collaborative transformation is also shaped by deeper symbolic and cultural structures. Following Maggs (2024a) and Vervaeke (2019), symbolic infrastructure refers to shared narratives, symbols, aesthetic experiences, and value structures that orient collective perception and action. These symbolic systems provide interpretive scaffolding through which collaborative insights become socially meaningful.

Artistic interventions often play a critical role in constructing symbolic infrastructures. Olafur Eliasson's Ice Watch (2014), for example, brought glacial ice into urban environments, transforming distant climate data into embodied encounters. Such works demonstrate how artistic practices can connect perception, affect, and action—dynamics often central to complex adaptive systems (Cilliers, 2000; Meadows, 2008).

Symbolic infrastructures therefore operate not merely as communicative devices but as meaning-making systems that shape collective orientation and future action.

2.5.2 Conditions Supporting Transdisciplinary Collaboration

While the mechanisms discussed above mediate collaboration across epistemic boundaries, their effectiveness depends on the broader relational and epistemic conditions within which collaboration unfolds.

2.5.2.1 Epistemic Reflexivity

Transdisciplinary collaboration also requires participants to engage reflexively with their own disciplinary assumptions. *Epistemic reflexivity* involves deliberate reflection on how knowledge is produced, validated, and communicated within specific epistemic traditions.

Drawing on Gardiner's (2020) framework, epistemic reflexivity includes four interrelated capacities: epistemic awareness, humility, empathy, and epistemic control. Together, these capacities support collaborative environments in which participants can recognise disciplinary differences while remaining open to alternative ways of knowing.

Building on Gardiner's framework, this research proposes a fifth dimension—*epistemic innovation*—to describe the emergence of new ways of knowing that arise from sustained cross-disciplinary engagement.

2.5.2.2 Productive Friction

Isabelle Stengers' philosophy offers an influential framework for understanding how tensions between disciplinary perspectives can function as productive conditions for collaborative inquiry. Rather than treating friction as an obstacle, Stengers conceptualises it as a generative force enabling transformation across epistemic communities (Stengers, 2011, 2018).

Central to Stengers' approach is the practice of *slowing down*—creating moments of hesitation that allow participants to question assumptions and respond more attentively to others' perspectives (Stengers, 2005b). Such pauses resist premature closure and maintain multiple perspectives in productive tension.

Within transdisciplinary collaboration, *productive friction points* arise when differing disciplinary assumptions generate temporary misalignment. When appropriately scaffolded through critique, debate, contrasting interpretation, and reflective dialogue, these moments can catalyse deeper inquiry and support the emergence of integrated understanding (Dewey, 1934; Engeström, 2015; Schon, 1983).

2.5.2.3 Trust and Psychological Safety

For friction to remain generative rather than destructive, collaborative environments require sufficient trust and psychological safety. While these constructs are closely related, they operate at different but interconnected levels within collaborative processes. Trust functions primarily as a relational mechanism between participants, whereas psychological safety reflects a broader collaborative climate that enables interpersonal and epistemic risk-taking.

Trust operates both relationally and epistemically, shaping whether participants feel able to share emerging ideas and question disciplinary assumptions. Levin & Cross (2004) distinguish two forms of trust central to collaboration: *benevolence-based trust*, referring to confidence in collaborators' intentions, openness, and mutual goodwill, and *competence-based trust*, referring to confidence in their expertise and ability to contribute meaningful knowledge. Within transdisciplinary contexts, these forms of trust influence participants' willingness to expose uncertainty, engage across disciplinary boundaries, accept critique, and remain open to epistemic challenge.

Psychological safety further supports collaboration by enabling participants to voice tentative, incomplete, or unconventional ideas without fear of ridicule, dismissal, or interpersonal sanction (Edmondson, 2012). Amy Edmondson (2012) defines psychological safety as a shared belief that a group is safe for interpersonal risk-taking. Unlike trust, which concerns expectations between individuals, psychological safety emerges at the group level through the interaction of relational trust and broader structural conditions, including facilitation practices, norms of dialogue, critique structures, iterative collaboration, and the wider learning or studio culture.

The relationship between these constructs is therefore developmental rather than synonymous. Benevolence-based trust appeared closely linked to participants' willingness to express uncertainty, tolerate ambiguity, expose incomplete ideas, and engage productively with friction. When sufficient trust is present, disagreement can be approached constructively, allowing cognitive conflict to stimulate innovation rather than dysfunction (Jehn, 1995). Trust therefore constitutes a foundational relational condition through which psychological safety can emerge, supporting epistemic risk-taking and productive transdisciplinary engagement.

Trust, therefore, constitutes a foundational relational condition for productive transdisciplinary collaboration

2.5.2.4 Mutual Learning in Community of Practice (CoP)

Situated learning theory conceptualises learning as participation in communities of practice Lave & Wenger, 1991; Wenger, 1998). Within such communities, knowledge develops through social interaction rather than isolated individual cognition.

In transdisciplinary settings, communities of practice support mutual learning by enabling participants to engage with diverse epistemic traditions. Through participation, newcomers gradually move from peripheral involvement toward fuller participation in shared practices.

These collaborative learning ecologies support identity formation, shared understanding, and the development of new knowledge practices.

2.5.2.5 Ambiguity Tolerance

Transdisciplinary collaboration often involves complex, open-ended problems characterised by uncertainty and incomplete information. Artistic practices frequently cultivate tolerance for such ambiguity by engaging multiple interpretations rather than seeking premature closure (Eisner, 2002a; Hetland, 2013).

Design research similarly emphasises the productive role of ambiguity in creative inquiry. Open-ended challenges encourage abductive reasoning and conceptual reframing, enabling innovative connections across domains (Cross, 2006; Dorst, 2019; Kolko, 2010).

Maintaining openness during early stages of inquiry therefore supports creativity and adaptive problem solving in transdisciplinary contexts.

2.5.3 Arts as Transformative Epistemic and Ontological Agents

Across arts-based research, STEAM education, and art–science collaboration literature, artistic practices are increasingly understood not as supplementary activities but as epistemic and ontological agents capable of generating new forms of knowledge (Barone & Eisner, 2012; Eisner, 2002a; Galafassi, 2018; Leavy, 2020).

Artistic practices can surface tacit knowledge, challenge epistemic hierarchies, and create imaginative spaces for transdisciplinary exploration. Practices such as storytelling, critique, speculative futures, and critical making engage imagination, affect, and ethical reflection while supporting collaborative inquiry.

Through these processes, artistic practices contribute not only to collaborative dynamics but also to the emergence of integrative forms of knowledge that extend beyond the boundaries of individual disciplines.

2.5.4 Aesthetic and Embodied Modes of Inquiry

2.5.4.1 Transdisciplinary Cognitive Skills

Creativity research further suggests that scientists, artists, and engineers share common cognitive tools for creative thinking (Root-Bernstein & Root-Bernstein, 2001). Henriksen & Group (2018) synthesised these into seven Transdisciplinary Cognitive Skills (TCS): *perceiving, patterning, abstracting, embodied thinking, modelling, playing,* and *synthesising*. These capacities encompass processes of attentive observation, recognition of patterns, conceptual abstraction, embodied understanding, the construction of models, and exploratory experimentation through play. Together, these skills support movement from sensory perception to conceptual integration, enabling participants to explore, test, and reconfigure ideas within complex collaborative systems.

2.5.5 Toward a Pedagogical Architecture for Transdisciplinary Collaboration

The literatures reviewed in this section clarify that transdisciplinary collaboration does not arise spontaneously from disciplinary diversity. Rather, it depends on the interaction of multiple relational, epistemic, and mediating conditions. Trust establishes a relational foundation; productive friction introduces generative tension; epistemic reflexivity supports negotiation across disciplinary perspectives; communities of practice sustain mutual learning; and ambiguity enables exploratory reframing. Mediating mechanisms—including boundary objects, transformational creativity, and symbolic infrastructures—enable coordination, conceptual reframing, and the development of shared meaning across epistemic boundaries.

Although these mechanisms are discussed across diverse literatures—including science and technology studies, design research, and art–science collaboration—they have never been examined together within a coherent pedagogical architecture capable of intentionally scaffolding transdisciplinary collaboration.

The present research investigates how such mechanisms may be activated through pedagogical interventions in higher-education STEAM contexts. Chapter 3 introduces the methodological framework through which the Transdisciplinary STEAM Design Toolkit (TD-SDT) was developed and iteratively refined through cycles of pedagogical experimentation.

2.6 TD Assessment in Literature – Constructed Framework

Having examined conceptual mechanisms that support transdisciplinary collaboration, it is necessary to consider how such collaboration and its outcomes can be assessed.

In this dissertation, transdisciplinary collaboration refers to the collaborative processes through which participants bringing distinct disciplinary, experiential, and institutional forms of knowledge negotiate perspectives , coordinate forms of expertise, and develop shared or partially shared problem framings across epistemic boundaries. Knowledge creation refers to the emergence of new integrative insights, artifacts, or understandings that arise from these collaborative processes and extend beyond the contributions of individual disciplines.

Because the present research investigates how specific concepts and tools support transdisciplinary collaboration, an assessment framework is required to evaluate both collaborative processes and resulting knowledge outcomes. The following section therefore synthesises literature on transdisciplinary assessment to construct a framework appropriate to higher-education STEAM contexts.

The literature on transdisciplinary assessment (Binder et al., 2015; Hansson & Polk, 2018; Lang et al., 2012; Lux et al., 2019; Mansilla, 2006, 2016; Mansilla & Duraising, 2007; Pohl et al., 2021; Pohl & Hirsch Hadorn, 2008; Scholz & Steiner, 2015; Stokols, Misra, et al., 2008; Walter et al., 2007) provides a cross-disciplinary foundation for evaluating collaborative research across domains including team science, sustainability science, and collaborative design.

Collectively, these works suggest that assessing transdisciplinary collaboration requires moving beyond conventional disciplinary metrics toward three interrelated dimensions: *process quality, integration quality*, and *societal effects*. Process quality refers to the functioning of collaboration, including stakeholder engagement and the dynamics through which participants coordinate their work. Integration quality concerns the extent to which diverse disciplinary perspectives are meaningfully synthesised into coherent forms of knowledge. Societal effects capture learning outcomes and broader impacts, including participant capacity building and potential contributions to policy or practice. These dimensions provide a comprehensive basis for evaluating both the collaborative processes through which transdisciplinary work unfolds and the knowledge outcomes that emerge from such collaboration.

2.6.1 TD Assessment - Process Quality

Process quality relates to how the work is planned, executed, managed, and the effectiveness of the collaboration dynamics among researchers and practitioners, corresponding to our students in this study. The two dimensions of *process quality* assessed along with their respective subdimensions are the c*ollaborative process* (trust, communication, mutual learning, conflict handling, shared problem framing), and *reflexivity* (equal footing, power relationships & fairness, team critical self-awareness). More details on the assessment of the *process quality* through *Collaborative Process* and *Reflexivity* and their respective subdimensions with their suggested assessment methods are presented below.

Collaborative Process – Trust

Trust is commonly defined as “behavioural reliance on others under conditions of risk” Walter et al., 2007, p.332). Positive social interactions strengthen trust, while negative interactions weaken it (Binder et al., 2015). In collaborative settings, particularly those involving distributed or interdisciplinary teams, trust becomes essential because participants often lack shared norms or monitoring structures (Stokols, Hall, et al., 2008).

Trust may be assessed qualitatively through participant narratives and reflective accounts or quantitatively through survey instruments capturing willingness to reveal knowledge gaps, openness to critique, and respect for collaborators (Mâsse et al., 2008). High levels of trust are associated with greater willingness to cooperate and share knowledge within collaborative teams (Walter et al., 2007).

Communication

Effective collaboration requires agreed communication structures and decision-making processes, regularly evaluated to ensure continued functionality Bergmann et al., 2005). Dialogue-based self-evaluation further supports alignment and collective learning.

Assessment therefore examines whether communication practices enable coordination and mutual understanding among participants.

Mutual Learning

Mutual learning refers to learning across disciplinary boundaries through sustained interaction (Bergmann et al., 2005). It emerges when communication structures allow participants to exchange expertise and build shared understanding. Assessment focuses on whether collaboration facilitates interdisciplinary co-learning and experiential knowledge exchange.

Conflict Handling (Friction)

Conflict management involves evaluating whether strategies exist to address disagreements and whether reflexive forums allow differences to be negotiated productively (Lang et al., 2012). Rather than eliminating differences, effective TD collaboration maintains plurality while preventing destructive conflict escalation (Bergmann et al., 2005). Assessment therefore examines whether conflict contributes to productive epistemic negotiation.

Shared Problem Framing

Shared problem framing assesses whether collaborators develop a common understanding of the problem through discursive negotiation and whether boundary objects or shared research objects support integration across perspectives (Bergmann et al., 2005).

Reflexivity

Reflexive dimensions concern the extent to which collaboration allows participants to critically examine roles, status (equal footing), assumptions, fairness, and power relations. Assessment includes evaluation of fairness in participation, transparency of decision-making, and collective responsibility for equitable collaboration structures (Bergmann et al., 2005; Hansson & Polk, 2018).

Team critical self-awareness further examines whether teams engage in ongoing reflection regarding their collaborative functioning (Bergmann et al., 2005; Hansson & Polk, 2018).

In sum, Process Quality evaluates the effectiveness, fairness, and reflexive adaptability of collaborative dynamics during a project. It forms the first of three core dimensions for assessing *transdisciplinary collaboration, focusing on the rigour of the collaborative process. The remaining dimensions—Integration Quality and Societal Effects—address the coherence of knowledge integration and the real-world relevance and impact of outcomes, respectively.*

2.6.2 TD Assessment - Integration Quality

Integration quality concerns the epistemic character of interdisciplinary outcomes including prototypes and final artifacts. Three dimensions are emphasised: *disciplinary grounding*, *integration coherence*, and *advancement of understanding*.

Disciplinary grounding assesses whether contributions remain anchored in relevant disciplinary knowledge (Mansilla & Duraising, 2007). *Integration coherence* evaluates how effectively disciplinary insights are synthesised into a unified outcome (Mansilla, 2006). *Advancement of understanding* examines whether results generate insights unlikely to emerge from single disciplines alone (Mansilla, 2006).

Integration quality measures the substantive fusion of diverse knowledge bases, specifically requiring that new insights maintain consistency with disciplinary antecedents while achieving a balanced weaving of perspectives into a coherent, generative whole (Mansilla, 2006).

2.6.3 TD Assessment - Societal Effects

Societal effects concern impacts beyond collaboration itself, including participant learning and broader societal usefulness or policy influence (Bergmann et al., 2005; Hansson & Polk, 2018). Dimensions to assess *Societal effects* include *learning and capacity building*, *societal usefulness*, and *societal impacts* (Binder et al., 2015; Pohl & Hirsch Hadorn, 2008; Walter et al., 2007).

Societal effects gauge the influence of research outcomes beyond the scientific sphere, exemplified by *enhanced stakeholder decision-making capacity* concerning regional political issues, which is often mediated by gains in network building and transformation knowledge (Walter et al., 2007).

In educational contexts where projects remain primarily academic, assessment focuses primarily on participant learning and capacity development rather than direct policy or practice change.

2.6.4 Resulting TD Process Assessment Framework

Drawing on the reviewed literature, this study constructs a *TD Process Assessment Framework* (Table 3) encompassing three dimensions: TD process quality, TD integration quality, and TD societal effects. Process quality captures collaborative functioning; integration quality evaluates knowledge integration; and societal effects assess participant learning and potential broader impacts.

This framework provides the evaluative basis for examining how TD-SDT components contribute to TD collaboration and knowledge creation. Its operationalisation is presented in section 3.7, and empirical application appears in sections 5.2 to 5.4.4.3.

Table 3 TD Process Assessment Framework

TD Process Assessment Framework to assess TD Collaboration & TD Knowledge Creation			
TD Process Quality – TD Collaboration			**Citations**
	Collaborative Process	C1-Trust	(Walter et al., 2007), (Binder et al., 2015), (Mâsse et al., 2008)
		C2-Communication	(Bergmann et al., 2005)
		C3-Mutual Learning	(Bergmann et al., 2005)
		C4-Conflict Handling (Friction)	(Lang et al., 2012), (Bergmann et al., 2005)
		C5-Shared Problem Framing	(Bergmann et al., 2005)
	Reflexivity	C6-Equal footing, Power relationships & fairness	(Hansson & Polk, 2018), (Bergmann et al., 2005)
		C7-Team Critical Self-Awareness	(Hansson & Polk, 2018), (Bergmann et al., 2005)
TD Integration Quality – TD Knowledge Creation (Tangible)			
	Artifacts	K1- Epistemic (Disciplinary) Grounding	(Mansilla & Duraising, 2007)
		K2- Integration Depth & Coherence	(Mansilla & Duraising, 2007)
		K3- Advancement of Understanding (novelty)	(Mansilla & Duraising, 2007)
TD Societal Effects – TD Knowledge Creation (Intangible)			
	Learning & Capacity Building of Participants	K4- Cognitive, social & practical competencies	(Walter et al., 2007),(Binder et al., 2015)
	Societal Usefulness	K5- Salient, credible, legitimate, actionable	(Walter et al., 2007),(Binder et al., 2015), (Bergmann et al., 2005) , (Hansson & Polk, 2018)
	Societal Impacts	K6- Policy & Practices Change	(Bergmann et al., 2005)

Table 4 presents the relationship between the CSC Theoretical Framework and the TD Process Assessment Framework developed in this study.

Table 4 CSC Framework Mapping to TD Assessment Framework

CSC Framework as Theoretical Foundation for TD Process Assessment			
CSC Lens	**What It Explains**	**Process Implications**	**Knowledge Creation Implications**
Constructivism	Disciplinary realities are socially constructed and perspectival.	Supports C1 (Trust), C5 (Shared Problem Framing), C7 (Team Reflexivity)	Supports K1 (Disciplinary Grounding), K2 (Integration Depth), K4 (Learning & Capacity Building)
Systems Thinking	Complex problems arise from interacting subsystems and feedback loops.	Supports C3 (Mutual Learning), C5 (Shared Framing), C6 (Equal Participation)	Supports K2 (Integration Depth), K3 (Novelty), K5 (Societal Usefulness)
Complexity Theory	Collaboration functions as a complex adaptive system shaped by nonlinearity and emergence.	Supports C2 (Communication), C4 (Friction), C7 (Critical Self-Awareness)	Supports K3 (Novelty), K4 (Learning), K6 (Transformative Potential)

The following two sections introduce the key concepts that underpin the TD-SDT, followed by the key tools.

2.7 Opening New Modes of Inquiry: The Need for an Integrated Architecture.

This chapter examined the theoretical and conceptual foundations necessary for understanding transdisciplinary collaboration in STEAM contexts. A review of widely adopted frameworks—including Design Thinking, the Double Diamond model, and the Creative Enquiry Process—indicates that although these approaches provide useful procedural scaffolding and foster creative engagement, they offer limited guidance regarding the relational, epistemological, and ontological conditions required for sustained transdisciplinary knowledge creation. Existing models rarely address the cultivation of psychological safety and trust, the productive negotiation of disciplinary tensions, or the role of the arts as epistemic contributors within collaborative inquiry.

Collectively, these observations reveal a structural gap within existing STEAM frameworks. Although the literature identifies important collaborative mechanisms and emerging evaluation approaches, these elements remain conceptually dispersed and are rarely integrated within a coherent pedagogical architecture capable of systematically supporting transdisciplinary collaboration.

In response, this chapter synthesised insights from transdisciplinary research, design studies, and art–science collaboration literature to identify key conceptual mechanisms supporting collaborative knowledge creation. It also introduced the conceptual foundations of a *TD Process Assessment Framework*, developed to define and evaluate the conditions necessary for effective transdisciplinary collaboration and knowledge integration.

Building on these foundations, the present research develops and examines an integrated framework—the *Transdisciplinary STEAM Design Toolkit (TD-SDT)*—designed to operationalise these mechanisms within higher-education STEAM collaborations. Together, the TD-SDT and its associated assessment architecture link conceptual insights, pedagogical tools, and evaluation strategies within a unified framework.

With this conceptual groundwork established, Chapter 3 presents the methodological design of the study, explaining how the TD-SDT was developed, iteratively refined, and examined through cycles of action research.

Chapter 3 Methodology

3.1 Introduction

This chapter outlines the methodological approach used to develop, refine, and examine the Transdisciplinary STEAM Design Toolkit (TD-SDT). Building on the theoretical foundations established in Chapters 1 and 2, it explains how the study investigated transdisciplinary STEAM collaboration within authentic educational contexts.

The study was guided by the following research question: *What framework and tools can support transdisciplinary knowledge creation within higher education STEAM design collaborations where art and artists are central participants?*

To address this question, the chapter first presents the methodological architecture of the study and the rationale for adopting Action Research. It then situates the research within the institutional and pedagogical context of the University of Ottawa's engineering design courses, introduces the TD Process Assessment Framework as an analytic lens, outlines data collection and analysis procedures, and concludes with considerations of researcher–practitioner positionality. Together, these elements establish the methodological conditions through which the empirical evolution of the TD-SDT is examined.

3.2 Methodological Architecture

Building on the theoretical foundations established in Chapters 1 and 2, this section outlines the methodological architecture (see Figure 1) through which the Transdisciplinary STEAM Design Toolkit (TD-SDT) was developed, refined, and examined. As established in Section 1.3, the Constructivism–Systems Thinking–Complexity (CSC) framework provides the conceptual foundation for understanding transdisciplinary STEAM design as an adaptive process involving epistemic negotiation, systemic interdependence, and emergent collaboration. The present chapter focuses on how this framework informed the design and implementation of the research process.

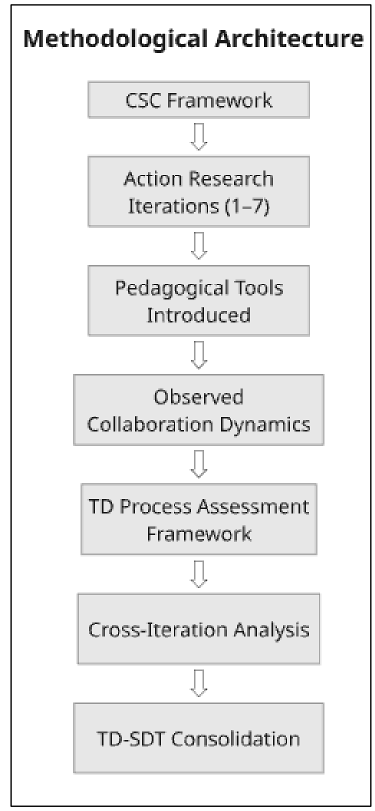


Figure 1 Methodological Architecture

This research emerged from the progressive integration of artistic practices into engineering design courses at the University of Ottawa beginning in 2017. These pedagogical interventions were designed not only to expose students to interdisciplinary collaboration but to examine how structured encounters across epistemic boundaries influenced collaboration dynamics, reflexive capacities, and integrative design outcomes. Across seven years (2017–2023), iterative course implementations generated a dataset documenting how students negotiated disciplinary assumptions, engaged with epistemic friction, and co-produced artifacts through STEAM-based collaboration.

To investigate this evolving process, the study adopted an Action Research (AR) methodology. Consistent with the CSC framing established in Chapter 1, the iterative structure of AR provided a methodological approach for examining transdisciplinary collaboration as an emergent and evolving process. The recurring cycles of plan, action, observe, and reflect enabled pedagogical interventions and collaborative conditions to be introduced, observed, and progressively refined across iterations.

Across seven cycles, pedagogical tools and conceptual elements were consolidated into what became the TD-SDT. While data were generated during instructional activities, the cross-iteration synthesis and validation of the toolkit were conducted between 2024 and 2025 using previously collected classroom data. This secondary analysis received approval from the University of Ottawa Research Ethics Board (Certificate of Ethics Approval #H 10-23-904; see APPENDIX A).

Consistent with the CSC framing introduced in Chapter 1, the study examined how pedagogical tools shaped collaborative dynamics, knowledge integration, and participant learning over time. Teams served as the primary unit of analysis, reflecting the collective nature of transdisciplinary work, while interviews, reflective journals, reports, artifacts, and researcher observations functioned as units of observation.

Importantly, the TD Process Assessment Framework used to analyse collaboration, and knowledge creation was developed following data collection. In action research and design-based inquiry, analytic frameworks frequently emerge from sustained engagement with practice, reflecting the co-evolution of theory and intervention rather than preceding it (A. L. Brown, 1992; Cobb et al., 2003). Although the framework was articulated after data collection, the dimensions it synthesises were already present in the theoretical literature reviewed in Chapter 2 and were observable in the empirical patterns emerging across the action-research iterations. Rigour in such approaches derives from transparency, triangulation, and systematic reconstruction rather than from temporal sequencing alone. Consistent with principles of action research and design-based inquiry, analytic dimensions were therefore consolidated through sustained engagement with both empirical data and the theoretical foundations reviewed in Chapter 2. Rather than imposing an evaluative structure a priori, the framework was inductively synthesised and then applied retrospectively as an analytic scaffold. Its operationalisation is detailed in Chapter 5.

3.3 Action Research Methodology Suitable for STEAM Disciplines

Action research was well suited to this study, as it aligned closely with the cyclical process required to iteratively improve each course iteration. Scholarly literature confirms that AR is a recognised and widely used methodology across STEAM disciplines as well as in educational research. In engineering and technological research, AR has been used to support iterative development and practice-based inquiry (Moirano et al., 2020). In education, AR is particularly relevant to situated learning contexts, a learning theory underpinning the design of the STEAM coursework examined in this study (McAteer, 2013).

The use of AR in education is grounded in constructivist learning theory, notably Dewey's (1934) emphasis on experience as central to knowledge generation, and in contemporary interpretations of experiential learning (Burns et al., 2021). AR is also closely aligned with practice-led artistic research—often referred to as research-creation—which positions practice itself as a mode of inquiry and knowledge production. Artistic research has been defined as a form of research in which scholarly inquiry and artistic practice are inextricably intertwined, and in which knowledge is generated through practice-based, practice-led, and practice-driven processes (Payne & Payne, 2004).

Methodologically, action research aligns directly with the CSC framework. Constructivism positions knowledge as co-constructed through experience; systems thinking emphasises iterative feedback loops; and complexity theory frames learning environments as adaptive systems evolving over time. The spiral structure of action research—planning, action, observation, reflection—mirrors these theoretical commitments by treating pedagogy as an evolving system rather than a fixed intervention.

Collectively, these theoretical and experiential alignments supported the selection of AR as an appropriate methodological framework for addressing the research question of this multidisciplinary STEAM study. Having established the suitability of AR, the following section defines how AR was conceptualised and implemented in this research.

3.4 Action Research Applied to this Study

Action research has been defined as research that identifies a social or practical problem and empirically tests a possible solution through iterative interventions monitored by systematic inquiry (Payne & Payne, 2004). It is characterised as inquiry conducted *by or with* participants, rather than *on* them, and as a deliberately reflexive and evidence-based process (Herr & Anderson, 2014). AR also emphasises professional learning, cyclical interventions, and critical self-reflection (Bhattacherjee, 2012; Johnson, 2008).

In this study, AR was operationalised as a spiral of action cycles involving planning, action, observation, and reflection (Johnson, 2008). The project comprised seven iterations, each conducted collaboratively by the teaching team and enrolled students.

The cyclical structure of action research mirrors the CSC framework articulated in Chapter 1. Constructivism is reflected in the co-construction of knowledge within classroom practice; systems thinking is enacted through iterative feedback across teams, tools, and contexts; and complexity theory is operationalised through the recognition of emergent collaboration patterns across iterations. In this way, the methodological design does not merely study transdisciplinary processes — it structurally enacts them.

Across all iterations, the central objective was the iterative development and refinement of TD-SDT components intended to support transdisciplinary knowledge creation. These components emerged and evolved across seven distinct real-world design contexts introduced by different external partners, thereby supporting their transferability and robustness.

The evolution of these iterations is analysed across Chapters 4 and 5, which document the consolidation of foundational components in Iterations 1–4 and their refinement and extension in Iterations 5–7. The resulting TD-SDT is presented in Chapter 6.

In sum, the action research methodology provided a robust framework for guiding the cyclical and reflexive evolution of the TD-SDT pursued in this study. The following section situates this methodological approach within the institutional and pedagogical context of the uOttawa engineering design courses and making environments in which the iterations were conducted.

3.5 Emergence of the Transdisciplinary STEAM Design Toolkit (TD-SDT)

The Transdisciplinary STEAM Design Toolkit (TD-SDT) was not introduced as a predefined intervention. Rather, it emerged progressively through the iterative cycles of the action research process.

Across the seven course iterations, pedagogical tools, facilitation strategies, and conceptual mechanisms were introduced, tested, and refined within authentic STEAM design contexts. Each iteration therefore functioned simultaneously as: a pedagogical intervention, an empirical observation site, a developmental stage in the construction of the toolkit.

Through the cycles of planning, action, observation, and reflection, patterns began to emerge regarding the conditions that enabled or constrained transdisciplinary collaboration and knowledge creation. Tools—such as structured reflection prompts, boundary-object exercises, philosophical concepts for reflection, and co-creation practices—appeared to activate specific collaborative mechanisms, including epistemic reflexivity, productive friction, and mutual learning.

Over time, these observations enabled the progressive consolidation of the TD-SDT as a *conceptual–pedagogical architecture* composed of *conceptual mechanisms* supporting TD collaboration and knowledge creation; *pedagogical tools* capable of activating those mechanisms within STEAM learning environments ; *design conditions* that enable these tools to function effectively.

Rather than representing a fixed set of activities, the TD-SDT therefore synthesises patterns observed across the seven iterations. Individual tools should be understood as *representative examples* of broader design conditions rather than as prescriptive elements.

Chapters 4 and 5 trace the empirical evolution of these elements across iterations, while Chapter 6 presents the consolidated TD-SDT architecture.

3.6 uOttawa Engineering Design Courses and Making Environments

This section describes the composition of the University of Ottawa first-year engineering design course, which served as the curricular foundation for the subsequent development of the STEAM design courses examined in this research. It first outlines key pedagogical and infrastructural elements used in the course, followed by a description of the course structure.

3.6.1 ITP Metrics for Personality Testing and Peer Feedback

ITP Metrics is a free online assessment platform developed by the Individual and Team Performance (ITP) Lab at the University of Calgary. The platform includes several tools, notably a Big Five personality assessment and a peer feedback system (O'Neill et al., 2019).

The Big Five assessment measures openness, conscientiousness, extraversion, agreeableness, and neuroticism through 120 Likert-scale questions, with scores ranging from 0 (low) to 1 (high) (Boudreau, 2021). The peer feedback system supports round-robin evaluations of individual and team effectiveness across five dimensions: communication, commitment, knowledge base, skills and abilities, and performance focus (O'Neill et al., 2019). Students evaluated themselves, their teammates, and their team overall, receiving anonymised feedback intended to support reflection and improvement (Boudreau, 2021).

ITP Metrics was used in the engineering design courses and as described in Chapter 4, also supported team formation and team dynamics within the STEAM Design courses examined in this study.

3.6.2 Group Contract

A group contract is a collaboratively authored agreement developed at the start of a project to define shared goals, roles, expectations, and communication norms. Group contracts supported accountability, clarified responsibilities, and helped mitigate conflict by making collaboration norms explicit (Boudreau, 2021).

3.6.3 Centre for Entrepreneurship and Engineering Design (CEED)

The University of Ottawa's Centre for Entrepreneurship and Engineering Design (CEED) comprises seven facilities, including a makerspace, a traditional machine shop, and specialised training areas for digital and physical fabrication. These spaces are open to undergraduate and graduate students throughout the week and to the public on Sundays. Engineering design courses made extensive use of CEED facilities, embedding hands-on prototyping into the curriculum and enabling rapid iteration and experiential learning (Boudreau, 2021).

3.6.4 Annual Makerspace Challenge

The CEED makerspace hosts a biannual design competition offering a $1,000 prize for winning student prototypes. The 2018 edition focused on interactive art, as discussed in Chapter 4 (Iterations 2 and 3). These challenges provided opportunities for extracurricular experimentation and fostered participation in a broader community of practice (Boudreau, 2021).

3.6.5 Design Day

Design Day is a biannual public showcase that connects students, faculty, industry professionals, and clients. It provides a platform for presenting design projects developed through coursework, research, or personal initiatives and includes external evaluation and awards (University of Ottawa, 2025).

3.6.6 University of Ottawa Engineering Design Course Structure

At the University of Ottawa, engineering students were introduced to design practices through a mandatory first-year course emphasing *client-centred*, team-based design. Students formed multidisciplinary teams, completed personality assessments, developed group contracts, and worked with *real clients* over a semester-long design cycle. The course integrated lectures, laboratories, prototyping activities, and multiple client feedback sessions. Prototyping primarily occurred in CEED facilities, culminating in public presentation at Design Day.

This structured, prototype-driven environment generated rich data on teamwork, collaboration, iterative decision-making, and learning—elements directly relevant to examining transdisciplinary collaboration and knowledge creation. (Boudreau, 2021).

The following sections describe how data were collected, organised, and analysed for the purposes of this research.

3.7 TD Process Assessment Framework (Analytical Lens)

Chapter 2 reviewed multiple theoretical strands relevant to transdisciplinary collaboration—including trust, friction, reflexivity, boundary objects, and integration theory—yet demonstrated that these mechanisms are rarely operationalised within a coherent design-and-assessment architecture. The TD Process Assessment Framework consolidates these strands into an integrative analytic structure for examining transdisciplinary collaboration and knowledge creation.

This section introduces the TD Process Assessment Framework as the conceptual and methodological lens used in this research to examine TD collaboration and TD knowledge creation within STEAM design contexts. While the theoretical foundations informing the framework were established in Section 2.6, the purpose of this section is to clarify how the framework functions within the research design—specifically, how it structures observation, data collection, and subsequent analysis across the action-research iterations. Its full operationalisation and empirical analysis are presented in Sections 5.2 to 5.4.4.3.

The TD Process Assessment Framework serves a dual role in this research. First, it functions as a methodological instrument, guiding the systematic examination of TD processes as they unfold within student teams. Second, it constitutes a research contribution, proposing an integrative and practice-sensitive way to conceptualise and assess TD collaboration and TD knowledge creation in educational STEAM settings. In keeping with action research principles, the framework is introduced here in a conceptual form and later refined, operationalised, and examined empirically through iterative application.

3.7.1 Purpose and Scope of the Framework

The framework was developed post hoc (Glaser & Strauss, 1998) to support the examination of how TD knowledge creation emerges through collaborative processes. Although the framework was articulated after data collection, the dimensions it synthesises were already present in the theoretical literature reviewed in Section 2.5 and were observable in the empirical patterns emerging across the action-research iterations. It responds to limitations identified in the literature, where TD collaboration, integration, and learning are often discussed conceptually but assessed inconsistently or not at all. In contrast, this framework enables TD processes to be systematically reconstructed and traced retrospectively across time, teams, tools, and iterations.

Within this study, the framework provides a structured way to examine *how teams negotiate epistemic differences and disciplinary assumptions; how collaborative dynamics enable or constrain integration; and how learning and capacity building emerge alongside tangible design outputs.* Importantly, the framework does not prescribe an idealised model of transdisciplinary work. Instead, it articulates dimensions of observation that allow variation, tension, and partial integration to be meaningfully documented and compared across contexts.

3.7.2 Conceptual Structure of the TD Process Assessment Framework

As summarised in Table 5, the TD Process Assessment Framework distinguishes three interrelated dimensions for examining TD collaboration and knowledge creation.

Table 5 TD Process Assessment Framework: Conceptual Dimensions

TD Process Assessment Framework to assess TD Collaboration & TD Knowledge Creation		
TD Process Quality – TD Collaboration		
	Collaborative Process	C1- Trust
		C2- Communication
		C3- Mutual Learning
		C4- Conflict Handling (Friction)

		C5- Shared Problem Framing
	Reflexivity	C6- Equal footing, Power relationships & fairness
		C7- Team Critical Self-Awareness
TD Integration Quality – TD Knowledge Creation (Tangible)		
	Artifacts	K1- Epistemic (Disciplinary) Grounding
		K2- Integration Depth & Coherence
		K3- Advancement of Understanding (novelty)
TD Societal Effects – TD Knowledge Creation (Intangible)		
	Learning & Capacity Building of Participants	K4- Cognitive, social & practical competencies
	Societal Usefulness	K5- Salient, credible, legitimate, actionable
	Societal Impacts	K6- Policy & Practices Change

Note. The framework is conceptually introduced here and operationalised and analysed in Sections 5.2 to 5.4.4.3.

As shown in Table 5, the TD Process Assessment Framework distinguishes three interrelated dimensions through which transdisciplinary collaboration and knowledge creation are examined: collaborative process quality, integrative artifact development, and societal or participant-level effects.

Together, these dimensions conceptualise TD knowledge creation as an emergent interaction among collaborative quality, integrative artifact development, and participant learning, rather than as a linear progression from teamwork to output.

In this research, student work remained primarily academic and did not involve field implementation with external stakeholders. Consequently, societal usefulness and societal impacts (K5–K6) were not empirically assessed, while learning and capacity building (K4) functioned as the primary intangible outcome dimension.

3.5.3 Role of the Framework in Research Design

Within this research, the TD Process Assessment Framework informed multiple stages of the study through a retrospective and reflexive application consistent with action research principles. Although the framework was developed after the experimental interventions and primary data collection had taken place, it was constructed through iterative engagement with both the empirical data and the theoretical foundations reviewed in Section 2.5. The framework was subsequently used to systematically organise and interpret interview transcripts, reflective journals, observational records, and material outputs, providing a shared analytical vocabulary for examining TD collaboration and TD knowledge creation across teams and iterations.

At this stage, the framework is intentionally presented without operational detail. Decisions regarding coding schemes, scoring rubrics, scales, and triangulation procedures are deferred to Section 5.2, where the framework is fully operationalised and empirically applied. This separation ensures a clear distinction between conceptual design positioning (Section 3.7) and methodological execution and validation (Sections 5.3 to 5.4.4.3), while preserving coherence across the research process.

By introducing the TD Process Assessment Framework here as both a methodological lens and an emerging research contribution, this chapter establishes the conditions under which data analysis can meaningfully examine how TD-SDT components support TD collaboration and TD knowledge creation.

This approach is coherent with action research and related qualitative methodologies, where analytic frameworks and assessment instruments commonly emerge from practice and data analysis, with rigor grounded in transparency and triangulation rather than in the prior existence of fixed evaluative tools (Ayton et al., 2023).

3.7.3 Overview of the TD Process Assessment Workflow

The *TD Process Assessment workflow* shown in Figure 2 is organised into five sections: *Initial Data, Team-Level Data Analyses A* and *B* (procedures repeated for each team), *Iteration-Level Data Analyses* (procedures repeated for each iteration), and *Triangulation* procedures used to strengthen and validate analytical results.

The *Initial Data* section presents the elements used in the workflow: the TD Process Assessment Framework established theoretically in Section 2.6; text-based student data collected during each action research (AR) iteration (reflective journals, interviews, and final reports); prototypes produced by each team; and the researcher's reflective journal for the iteration. Section 3.8 *Data Collection* details the content and collection procedures for these sources.

Team-Level Data Analyses A presents analytical procedures applied to each team, including mixed-methods analysis combining hybrid deductive–inductive thematic coding, prototype integration quality analysis, and critical incident analysis. Section 3.9 describes these data analysis methods in detail.

Text-based sources were analysed in three ways:

1. deductive coding using the TD Process Codebook to assess TD processes (APPENDIX F);
2. deductive coding to assess tool contributions; and
3. inductive coding to identify general discussion topics within each iteration.

Each prototype's TD Integration Quality (TIQ) was assessed using three dimensions: K1—Disciplinary Grounding, K2—Integration Depth and Coherence, and K3—Advancement of Understanding (Novelty), scored using rubric-based criteria (APPENDIX I,APPENDIX J,APPENDIX K). The researcher's reflective journal was analysed to identify key events and contextual factors informing the TD Process assessment through triangulation.

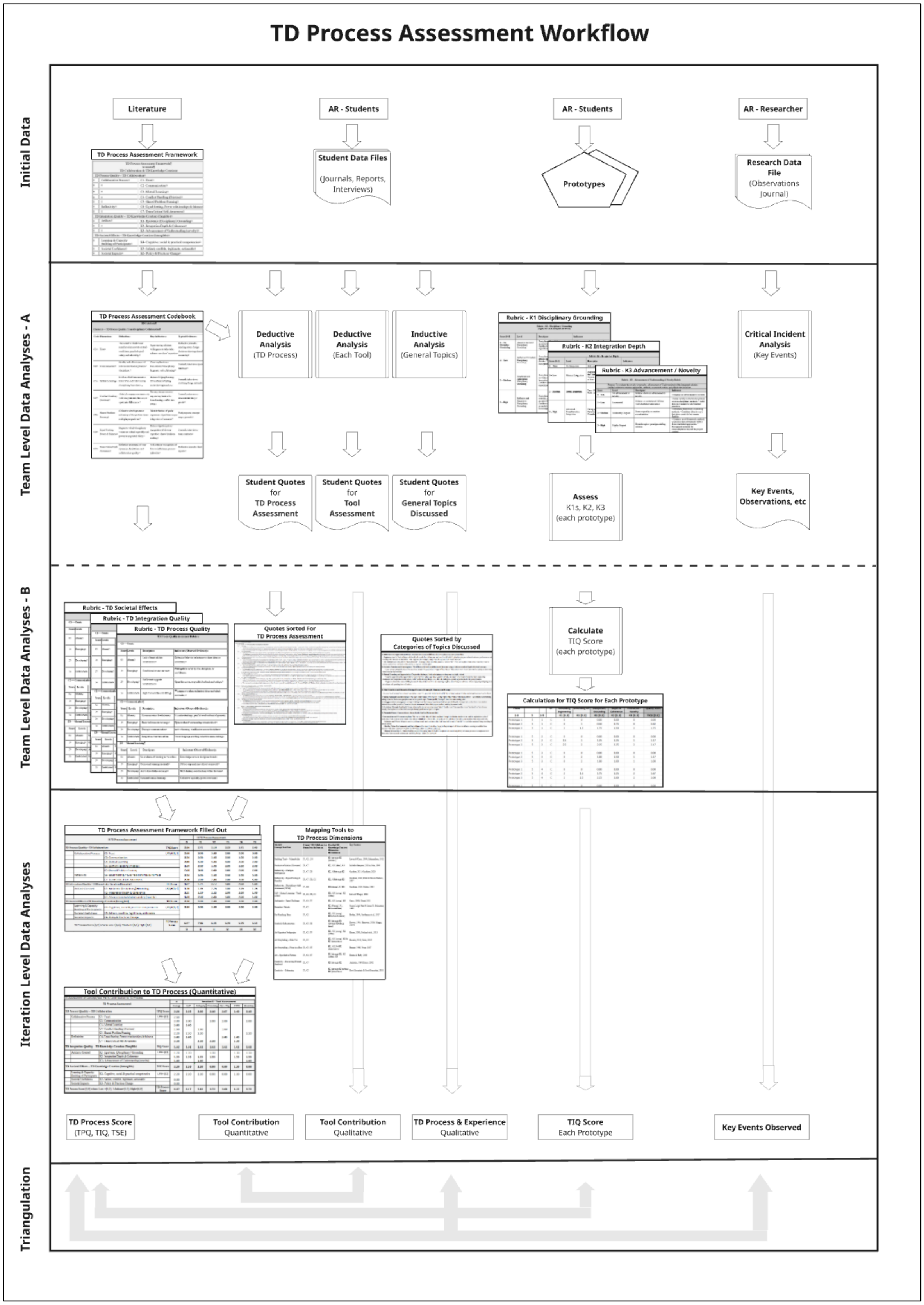


Figure 2 TD Process Assessment Workflow

Inductively coded quotations were grouped into emerging thematic categories that supported triangulation and informed interpretation of TD processes and student experiences. Prototype K1–K3 scores were then combined to produce prototype TIQ values.

The Iteration-Level Data Analyses section aggregates TD Process and tool assessments. Once team-level frameworks were completed, TPQ, TIQ, TSE, and overall TDP scores were calculated and interpreted at the iteration level. Using mappings between tools and TD Process dimensions, tool contributions were likewise calculated and interpreted.

Team- and iteration-level analyses yielded:

1. TD Process assessments at team and iteration levels.
2. quantitative assessments of tool contributions.
3. qualitative tool contribution evidence from student quotations.
4. emergent discussion topics and associated quotations.
5. TIQ scores for each prototype; and
6. key researcher observations.

Finally, the Triangulation section identifies which outputs were compared to strengthen interpretation through cross-validation of findings.

This TD Process Assessment workflow is fully operationalised and applied in Sections 5.2 to 5.4.4.3.

3.7.4 Tool Assessment Using TD Process Assessment Dimensions

The analysis of tool contributions to TD collaboration and TD knowledge creation draws on TD Process Assessment dimensions that were theoretically expected to be activated, as established in Section 2.4. APPENDIX L presents this mapping, identifying for each concept–tool pair (a) the primary TD collaboration dimensions and (b) the primary TD knowledge creation dimensions it supports, along with key supporting sources. This mapping provides the theoretical foundation for the contribution analysis presented in Section 5.2.4.

The following section describes the data collection methods used in this research.

3.8 Data Collection

This research draws on a rich body of qualitative and material data generated through STEAM Design courses delivered at the University of Ottawa between 2017 and 2023. The use of these anonymised data for research purposes was approved by the University Research Ethics Board (approval #H-10-23-904; see APPENDIX A). The dataset comprises textual materials—including semi-structured interviews, student reflective journals, team final reports, and researcher observation journals—as well as project outputs such as prototypes and final artifacts. These data were systematically analysed to examine the impact of the various TD-SDT components introduced across iterations—such as Lego Serious Play and open challenges—on transdisciplinary collaboration and knowledge creation.

In this research, a clear distinction is maintained between the unit of analysis and the units of observation. The *team* constitutes the primary *unit of analysis*, as TD collaboration and TD knowledge creation are conceptualised as emergent collective processes. Empirical data, however, were generated from multiple *units of observation*, including individual semi-structured interviews, student reflective journals, team final reports, prototypes, final artifacts and researcher reflective journals. These heterogeneous observational units were designed to enable triangulation at the team level, ensuring that subsequent analytical judgments could be grounded in convergent qualitative and material evidence while preserving traceability between individual experience, collective dynamics, and iteration-level outcomes.

A total of 367 data sources were collected and analysed in this research. As shown in Table 6, these data were gathered across seven iterations and involved 36 project teams comprising 152 students: 41 from the arts, 94 from engineering, and 18 from other disciplines, including Biology and Digital Transformation and Innovation (DTI). The participant cohort included 68 female and 84 male students.

The individual-level data sources consisted of seven semi-structured interviews and 216 individual reflective journal entries, which were consolidated into 61 compiled journals corresponding to contributing students. The full set of reflective journal questions is provided in APPENDIX O. In addition, 32 final reports, 68 intermediary prototypes, 37 final artifacts, and seven researcher observation journals were collected and analysed.

Table 6 Total Data Sources Collected for This Research

Iterations 1 to 7 - Data Collected													
Identification								**Individual Data**		**Team Data**			**Researcher Data**
Iteration	Teams	N Students	A	E	O	F	M	Journals	Collated Journals	Final Reports	Prototypes	Final Artifacts	Journals
1	4	7	0	8	0	1	6	0	0	0	0	4	1
2	8	35	0	35	0	8	27	0	0	8	16	8	1
3	2	11	4	6	1	5	6	1*	0	2	5	2	1
4	7	31	15	16	0	16	15	6*	0	7	14	6	1
5	5	20	7	13	0	11	9	57	16	5	12	6	1
6	4	22	6	8	8	12	10	76	21	4	9	5	1
7	6	26	9	8	9	15	11	83	24	6	12	6	1
7	36	152	41	94	18	68	84	216	61	32	68	37	7

*semi-structured Interviews

Together, these data sources provide a rich, multi-layered account of both the collaborative processes and knowledge creation outcomes that emerged across the seven action-research iterations. By combining individual, team-based, material, and researcher-generated data, this study captures transdisciplinary work which unfolded cognitively, socially, and materially over time.

The following subsections detail how these data sources were generated across the action-research cycles. They describe the specific data collection methods employed, the conditions under which data were gathered, and the procedures used to ensure consistency, ethical compliance, and methodological rigour. While these data were collected prior to the formal articulation of the TD Process Assessment Framework, they were generated through pedagogical and reflective practices that foregrounded collaboration, learning, and integration, enabling their subsequent systematic organisation and interpretation using the framework.

3.8.1 Semi-Structured Interviews

Semi-structured interviews were conducted in Iterations 3 and 4 to gain in-depth insight into students' perceptions of the STEAM learning environment and the perceived impact of the course on their collaborative practices and disciplinary development. This method was selected because semi-structured interviews are well suited to exploring complex, layered, and emergent experiences while allowing for probing and clarification of meaning (Barriball & While, 1994).

The interviews invited students to reflect on their collaborative experiences, team dynamics, learning processes, and perceived outcomes of the course. During analysis, interview data were subsequently examined in relation to dimensions of TD collaboration—such as trust, communication, mutual learning, friction, shared problem framing, and reflexive awareness of team dynamics (C1–C7)—as well as TD knowledge creation, including integration of disciplinary perspectives (K2), perceived novelty or advancement of understanding (K3), and learning and capacity building (K4).

To enhance clarity and coherence, the interview guide was piloted with two student teams prior to full deployment (see APPENDIX N). To reduce potential instructional bias, interviews were conducted by a researcher who was not part of the teaching team. Interviews took place outside the studio environment at the end of the semester and averaged approximately 40 minutes. One team from each course section was interviewed to ensure representation across disciplinary backgrounds and collaborative experiences.

Rigour was supported using a consistent interview protocol, pilot testing, neutral facilitation, and systematic retrospective coding using the TD Process Assessment Framework, enabling analytic comparability across teams and iterations.

3.8.2 Student Reflective Journals

Student reflective journals constituted a central data source for examining how engagement with TD-SDT tools shaped learning, collaboration, and the evolution of ideas over time. Reflective journaling supports metacognitive engagement by enabling participants to articulate their thinking as they move from uncertainty toward understanding (J. S. Brown et al., 1989). Longitudinal journal entries make visible the development of insight, the negotiation of disciplinary differences, and the emergence of integrative thinking (J. S. Brown et al., 1989).

These journals were retrospectively analysed to trace TD collaboration dynamics, including evolving trust, communication patterns, moments of friction, mutual learning, and reflexive awareness of team functioning (C1–C7). They also provided rich evidence of TD knowledge creation, particularly epistemic grounding (K1), integration depth and coherence (K2), conceptual breakthroughs or novelty (K3), and individual learning and capacity building (K4).

The journals captured students' internal reasoning, emotional responses, recognition of disciplinary boundaries, and reflections on tool use, enabling these lived experiences to be systematically organised and interpreted in relation to the TD Process Assessment Framework (see APPENDIX N for journal questions). Rigour was ensured through systematic collation of entries, and iterative coding procedures that enabled comparison both within and across teams.

3.8.3 Team Final Reports

Team final reports provided structured written accounts of problem framing, design rationale, iterative decision-making, feedback integration, and collective reflection. These reports were retrospectively analysed to examine shared problem framing (C5), evidence of negotiated integration across disciplines (K2), epistemic grounding (K1), and the extent to which teams articulated the societal relevance and intended usefulness of their outcomes (K5).

As synthesised team-level documents, final reports enabled triangulation between individual reflections and material outputs. Analytical rigour was supported using a consistent reporting structure across teams and systematic cross-referencing with other data sources.

3.8.4 Design Prototypes & Final Artifacts

Design prototypes and final artifacts produced during the STEAM Design courses and summer internships formed a key component of the dataset. These materials—including physical prototypes, digital models, sketches, sound compositions, and interactive installations—provided tangible evidence of the iterative design process and the degree of transdisciplinary integration achieved by each team.

Prototypes were retrospectively analysed as evolving boundary objects, revealing how ideas developed through iterative cycles, how disciplinary contributions were negotiated, and where integrative thinking emerged or stalled. Final artifacts—such as interactive installations, multimedia works, and refined physical prototypes—captured the culmination of these processes and were assessed in relation to epistemic grounding (K1), integration depth and coherence (K2), advancement of understanding or novelty (K3), and contextual and societal relevance (K5).

Consistent with transdisciplinary design pedagogy, the analysis prioritised the process revealed by these artifacts rather than the final product alone (Carter et al., 2021). Visual materials—including photographs, videos, diagrams, and sketches—were incorporated to capture tacit dimensions of collaboration and meaning-making that were not always articulated in textual data.

Rigour was ensured through systematic documentation, cross-iteration comparison, and triangulation with interviews, journals, and reports.

3.8.5 Researcher Reflective Journal

Action research literature recommends that researchers maintain a reflective journal to document events, decisions, emotional responses, and emergent insights throughout the research process (McAteer, 2013; Moon, 2006). Such journals support reflexivity by enabling researchers to interrogate assumptions, surface tensions, and trace evolving interpretations.

In this study, the researcher's reflective journal served as a longitudinal record of methodological decision-making, instructional interventions, and observed team dynamics across iterations. It was used to identify critical incidents (McAteer, 2013), trace shifts in TD collaboration processes (C1–C7), and capture early signs of conceptual emergence—such as epistemic friction—that were later consolidated and formalised within the TD Process Assessment Framework and TD-SDT coding structures (Section 5.2.2).

The journal also documented informal exchanges within the teaching team, capturing collective sensemaking around unfolding team dynamics and tool engagement. Rigour was supported through regular, dated entries, explicit differentiation between description and interpretation, and analytic integration with other data sources.

3.8.6 Data Collection - Summary

Together, these data sources provided a comprehensive and triangulated record of collaborative processes, epistemic negotiations, and material manifestations of TD Collaboration and TD knowledge creation. Although the TD Process Assessment Framework was articulated after data collection, the richness and reflexive nature of these data enabled their systematic retrospective organisation and analysis in relation to TD collaboration and TD knowledge creation dimensions. The use of multiple, complementary data types supports analytic rigour through triangulation, reflexivity, and cross-iteration comparison. The following section outlines the analytical procedures used to examine these data using the TD Process Assessment Framework.

3.9 Data Analysis

Consistent with the conceptual fragmentation identified in Chapter 2, analysis sought not only to evaluate outcomes, but to examine how relational, epistemic, and material mechanisms interacted within real classroom systems. Whereas Chapter 2 identified theoretical mechanisms in isolation, the present methodological design traces how such mechanisms converged, conflicted, and co-evolved across iterative cycles of practice. Given the longitudinal and process-oriented nature of TD collaboration and knowledge creation, analysis followed a qualitative, interpretive approach consistent with action research and constructivist inquiry.

Although the TD Process Assessment Framework was articulated after data collection, it was developed through iterative engagement with the empirical dataset and the theoretical foundations established in Chapter 2. The framework was then used retrospectively as an analytic scaffold to systematically organise and interpret evidence across text-based and material data sources. The operational workflow and scoring instruments used to implement the framework are presented in Chapter 5; the present section outlines the overarching analytic strategies applied to each data type.

Across iterations, three complementary analytic approaches were used:

- *Thematic analysis* of interviews, reflective journals, and team reports to examine TD collaboration dynamics and learning processes
- *Artifact-focused analysis* of prototypes and final outputs to examine integration quality and advancement of understanding embodied in tangible design work
- *Critical incident analysis* of the researcher's reflective journal to identify pivotal moments, shifts, and emerging insights across cycles

Rigour was strengthened through iterative coding and multi-source triangulation (see Triangulation section below).

3.9.1 Critical Incident Analysis

Critical incident analysis was used to examine the researcher's reflective journal and observational records. Critical incidents refer to events that mark significant turning points or changes in understanding and can only be recognised in retrospect through reflective judgement (Tripp, 1993). In action research, the identification of such incidents supports reflexive learning by making visible how interventions, interpretations, and facilitation strategies evolve over time (McAteer, 2013). In this study, critical incident analysis supported the identification of key moments related to team dynamics, facilitation decisions, and emergent TD collaboration patterns across iterations.

3.9.2 Artifact-Focused Analysis

Design prototypes and final artifacts were analysed as material traces of iterative design reasoning and epistemic negotiation. Because transdisciplinary integration is often expressed through evolving material decisions, prototypes were examined to identify how disciplinary contributions were blended, constrained, or transformed over time, and where integrative thinking emerged or stalled. Final artifacts were examined to assess the extent to which the resulting outputs evidenced epistemic grounding, integration depth and coherence, and advancement of understanding in relation to the disciplinary perspectives involved.

Operational metrics, rubrics, and scoring procedures used to assess integration quality are detailed in Section 5.2.

3.9.2.1 Formal Analysis for Artistic Quality Analysis

Formal analysis provides a structured framework for examining the elements and principles of art—such as form, materiality, spatial relationships, light, color, and texture—that shape aesthetic and conceptual experience. Its value lies in its capacity to systematically describe how these components function within a work and how they connect to broader critical, cultural, and theoretical contexts (Gombrich, 1960; Panofsky, 1939).

Rooted in art historical traditions, formal analysis foregrounds the material and visual dimensions through which meaning is often conveyed, particularly in installation and spatial practices (Gombrich, 1960; Panofsky, 1939). By attending closely to observable qualities, it enables grounded interpretation of aesthetic decisions and their effects. It is also well-suited to installation art, which frequently challenges medium-specific boundaries; formal analysis can account for this by examining how multiple media interact through spatial configuration, material choices, and participatory elements (Krauss, 1979).

Formal analysis further supports attention to viewer experience and interaction. As Bishop (2005) notes, installation art often shifts viewers into participants, requiring movement through space and time. A formal lens can therefore examine how scale, sequencing, and spatial design shape participation and meaning. Finally, formal analysis offers a comparative framework for situating works within historical and contemporary practices, and it provides a degree of rigor by grounding interpretation in descriptive evidence—supporting academic credibility without reducing art to purely objective measurement.

In the TD-SDT, formal analysis is positioned both as an evaluative lens for articulating artistic quality and as a pedagogical scaffold aligned with "perceiving"; its implementation and use as an assessment indicator are detailed in Chapters 4 and 5.

3.9.3 Inductive and Deductive Thematic Analysis

Text-based data (semi-structured interviews, student reflective journals, and team final reports) were analysed using thematic analysis to identify and interpret patterns related to TD collaboration and TD knowledge creation (Braun & Clarke, 2006). Coding followed an iterative and interpretive process appropriate to action research, enabling analysis of evolving collaboration dynamics and integrative processes across teams and iterations (Guest et al., 2011).

A hybrid inductive–deductive logic was used. Deductively, coding was informed by the Constructivism–Systems Thinking–Complexity (CSC) framework and by the dimensions consolidated within the TD Process Assessment Framework. Inductively, additional themes were allowed to emerge from the data. The resulting codebook was documented for transparency (APPENDIX F) and organised around TD collaboration and TD knowledge creation (tangible and intangible), supporting analytic consistency across iterations (Ridder et al., 2014).

3.9.4 Triangulation - Ensuring Analytic Rigour and Trustworthiness

To strengthen analytic credibility, this study employed triangulation across multiple complementary data sources collected within each action research iteration. Triangulation allowed interpretations of transdisciplinary collaboration and knowledge creation to be supported by converging evidence rather than relying on a single form of data (Denzin, 2002; Lincoln, 1985).

Each data source captured different aspects of the learning and collaboration process. Student reflective journals revealed individual reasoning, emotional responses, and perceptions of team dynamics; team final reports documented collective decision-making and shared problem framing; prototypes and final artifacts provided tangible evidence of disciplinary integration and design evolution; client critiques offered external perspectives on design quality and responsiveness; and researcher reflective journals captured classroom interactions and critical incidents as they unfolded. Semi-structured interviews, where available, further clarified how participants interpreted their experiences retrospectively.

During analysis, claims regarding collaboration dynamics or knowledge integration were validated by seeking convergence across at least two data sources whenever possible. For example, evidence of mutual learning or conflict negotiation was corroborated through journal reflections, team reports, and researcher's observational notes, while claims regarding integration quality were examined through both textual explanations and material outputs. When evidence diverged, discrepancies were treated as analytically significant, prompting further examination rather than being smoothed over.

This multi-source triangulation reduced dependence on any single perspective and enabled a richer reconstruction of how collaborative and epistemic processes unfolded across teams and iterations.

3.9.5 Data analysis - Summary

Together, these complementary analytic approaches enabled the study to examine TD processes as they unfolded cognitively, socially, and materially across the seven action-research iterations. By combining thematic analysis, artifact-focused analysis, and critical incident analysis, this study developed a robust evidentiary basis for examining how TD-SDT components supported (or constrained) TD collaboration and TD knowledge creation. As described above, triangulation across data sources strengthened interpretive credibility and supported cross-iteration comparison. Chapters 4 and 5 present the results of the cross-iteration analyses, and Chapter 5 details the operational implementation of the TD Process Assessment Framework used to support systematic comparison across teams and iterations.

Beyond analytic procedures and assessment frameworks, action research also requires explicit consideration of the researcher's position within the studied environment. Because this research unfolded within courses designed and facilitated by the researcher, interpretation of events, interventions, and outcomes cannot be fully separated from the researcher's pedagogical and professional engagement. The following section therefore clarifies the researcher–practitioner positionality that shaped both the design of interventions and the interpretation of resulting data.

3.10 Researcher–Practitioner Positionality

This research is grounded in the author's positionality as an educator, researcher, and practitioner. For more than two decades, the author has facilitated collaborations among artists, engineers, and students from multiple disciplines, working at the intersection of creative and technical practices.

Since 2017, artistic approaches have been progressively integrated into engineering design education at the University of Ottawa. Within this context, the author has designed and taught courses, experimented with pedagogical strategies, and examined how collaborative learning unfolds within authentic classroom environments. Occupying both teaching and research roles enables the systematic study of instructional practices while simultaneously refining them through iterative implementation.

This position provides close access to classroom dynamics, team interactions, and the ways in which students engage with tools, concepts, and collaborative processes. At the same time, it necessitates sustained reflexivity. Assumptions, instructional choices, and analytical interpretations must be continually examined to maintain methodological rigour.

The author's positionality aligns with the Constructivism–Systems Thinking–Complexity (CSC) framework that underpins this research. Constructivism views knowledge as co-constructed through interaction and experience. Systems thinking emphasises the relationships among people, tools, and contexts. Complexity theory understands collaborative learning environments as adaptive and evolving systems. From this perspective, teaching practice is not separate from inquiry; designing, facilitating, and reflecting are themselves forms of knowledge production.

Within a CSC framing, the researcher–practitioner role is therefore not treated as a bias to be eliminated but as a systemic element within the research ecology. Reflexivity consequently becomes not optional but methodologically necessary for interpreting the dynamics of transdisciplinary collaboration and learning.

3.11 Conclusion Chapter 3 - Methodology

This chapter has presented the methodological foundations guiding this research, which aimed to develop and examine a Transdisciplinary STEAM Design Toolkit (TD-SDT) designed to support transdisciplinary knowledge creation within STEAM collaborations.

The chapter established the suitability of Action Research for investigating and iteratively refining pedagogical interventions across diverse disciplinary contexts, and described how successive cycles of planning, action, observation, and reflection structured the evolution of STEAM-based interventions across seven course iterations. It also outlined the institutional and pedagogical environments in which the research unfolded, clarifying how engineering design courses and making environments provided authentic contexts for transdisciplinary collaboration.

The range of qualitative and material data collected—including semi-structured interviews, reflective journals, team reports, prototypes, artifacts, and researcher observations—was then presented alongside the analytic approaches used to examine collaborative processes and knowledge creation outcomes. Although the TD Process Assessment Framework was articulated after the completion of data collection, the richness and reflexive nature of the dataset enabled its subsequent systematic organisation and interpretation through that framework.

Together, this methodological architecture establishes the conditions for examining how TD-SDT components functioned across iterative cycles of practice. The following chapter traces the empirical evolution of these interventions across Iterations 1–4, while Chapter 5 operationalises and applies the TD Process Assessment Framework to enable systematic cross-iteration comparison.

In doing so, Chapter 3 operationalises the theoretical commitments articulated in Chapter 1 and the conceptual mechanisms synthesised in Chapter 2. The following chapter traces how these commitments unfolded empirically across iterative interventions, establishing the developmental foundations of the TD-SDT.

Chapter 4 Empirical Evolution and TD-SDT foundations – Iterations 1 to 4

4.1 Introduction and Reporting Structure

Applying the methodological framework outlined in Chapter 3, this present chapter examines the empirical evolution of the Transdisciplinary STEAM Design Toolkit (TD-SDT) across the first four iterations of a longitudinal classroom-based action research project. Drawing on data generated within authentic higher education STEAM contexts, it traces how core TD-SDT concepts and tools emerged, were tested, and were progressively refined in practice.

Together with Chapter 5, this section forms the empirical core of the thesis. The discussion here documents the developmental phase of the TD-SDT, illustrating how foundational components--such as trust-building mechanisms, epistemic reflexivity practices, productive friction, and boundary objects--took shape through iterative implementation, while Chapter 5 builds on this groundwork to introduce and operationalise the TD Process Assessment Framework for systematic cross-iteration evaluation.

The interventions described here took place within multidisciplinary STEAM design courses in which teams—often composed of artists and engineers—engaged with open-ended, real-world challenges requiring negotiation across epistemic boundaries. These classroom environments provided opportunities to observe how disciplinary assumptions were surfaced, how collaborative tensions were navigated, and how artistic practices functioned as active contributors to integrative knowledge creation. In doing so, this research responded to a persistent gap in the literature: the limited availability of documented pedagogical approaches capable of intentionally guiding multidisciplinary teams toward transdisciplinary knowledge creation while positioning the arts as epistemic partners.

Each cycle examined how particular pedagogical and conceptual interventions influenced collaboration dynamics and integrative outcomes under varying degrees of structure and ambiguity. Insights generated through iterative refinement progressively shaped the TD-SDT into a more coherent and intentional design infrastructure.

4.1.1 Reporting Structure

To enable the reader to trace this developmental trajectory, the chapter reports on Iterations 1–4 using the four canonical phases of action research: Plan, Act, Observe, and Reflect.

Each iteration begins with the *Plan* phase, which presents the course context, the STEAM design challenge, and the specific TD-SDT research focus guiding pedagogical and methodological inquiry. Planned activities and conceptual tools intended to support transdisciplinary knowledge creation are identified, along with the data collection strategies used to examine their influence.

The *Act* phase describes how classroom interventions were implemented, including facilitation strategies, adjustments made in response to emerging challenges, and the introduction of specific TD-SDT components. Modifications documented during implementation informed the design of subsequent iterations.

The *Observe* phase reports data collected during implementation. Student reflections, team reports, interviews, prototypes, and researcher observations were analysed using inductive and deductive thematic analysis. Artifacts were examined for evidence of disciplinary integration and conceptual synthesis. Representative excerpts and thematic summaries substantiate findings and highlight emerging patterns. Team numbers are retained as originally assigned during the course iterations to ensure consistency and traceability across reports, artefacts, observation notes, and quotations.

The *Reflect* phase synthesises insights from each iteration, evaluating how pedagogical interventions influenced collaboration processes and knowledge creation. These reflections guided decisions regarding which TD-SDT components were retained, refined, or redesigned in subsequent cycles.

Presenting each iteration through the Plan–Act–Observe–Reflect structure enables the reader to trace how and why TD-SDT components evolved over time. The sections that follow describe Iterations 1–4 using this structure, establishing the empirical foundations upon which the more systematic assessment presented in Chapter 5 is built.

This chapter examines the early empirical evolution of the Transdisciplinary STEAM Design Toolkit (TD-SDT) across the first four iterations of the action research process. Together with

Chapter 5, which reports Iterations 5–7, these sections document the progressive emergence of the framework.

4.2 Iteration 1 – Launch uOttawa STEAM (2017)

Iteration 1 served as an exploratory pilot aimed at bringing art and engineering students together through an extracurricular design challenge. The goal was to observe whether multidisciplinary collaboration could emerge organically with minimal facilitation. This initial iteration therefore provided a baseline for understanding participation dynamics, collaboration patterns, and the types of artefacts produced when students engaged in STEAM design with limited pedagogical scaffolding.

The opportunity arose when a muraled building on uOttawa's main campus was scheduled for demolition and replaced by a new STEM facility without budget for commissioned public art. Rather than viewing this constraint as a limitation, the initiative reframed it as an opportunity for students to collaboratively create interactive installations for the new space. This reframing aligns with affirmative ethics (Braidotti, 2019), transforming institutional constraints into opportunities for creative experimentation.

4.2.1 Plan - Iteration 1

4.2.1.1 STEAM Design Challenge and Research Focus

The *STEAM design challenge* asked whether an extracurricular initiative could bring engineering and arts students together to co-create interactive art installations for the new STEM building. The learning objective was to offer students an opportunity to experiment with interdisciplinary teamwork, creative prototyping, and public presentation.

In parallel, the *TD-SDT research focus* examined how multidisciplinary teams navigate epistemological and ontological differences between engineering and arts practices. Central questions included whether such collaborations could emerge without structured scaffolding and which concepts or tools might be necessary to support sustained engagement.

This iteration was co-developed by Hanan Anis (Engineering) and the author (Arts), with additional support from the Makerspace team (Section 3.6.3) and the Faculty of Arts. The twelve-week extracurricular challenge concluded with *Design Day*, the Faculty of Engineering's annual public showcase.

Key stakeholders included engineering and visual arts students, Makerspace staff, faculty leadership, and the Design Day organising committee, whose involvement provided institutional support and legitimacy.

4.2.1.2 Data Collection & Analysis Plan

Data collection was intentionally lightweight, reflecting the exploratory nature of this pilot. Sources included attendance records, organiser observation notes, informal student feedback, and prototypes exhibited at Design Day. The aim was not rigorous measurement but feasibility testing and identification of emergent dynamics informing future iterations.

Success was therefore evaluated primarily through the formation of multidisciplinary teams and the ability of collaborations to sustain themselves without explicit facilitation.

4.2.2 Act - Iteration 1

4.2.2.1 Implementation

The Makerspace Challenge was launched jointly by the engineering and arts faculties and promoted through university communication channels and faculty networks. To encourage participation, a casual pizza lunch was organised in the Visual Arts building as an accessible entry point for students.

Approximately thirty students attended the launch, evenly split between engineering and arts programs. However, although initial interest appeared balanced, only engineering students ultimately formed teams. Four engineering teams completed interactive installation prototypes and presented them at Design Day. No visual arts students participated beyond the initial event.

4.2.2.2 TD-SDT Components Studied

As an exploratory pilot, this iteration intentionally avoided prescriptive frameworks or structured facilitation. Interaction between disciplines was expected to emerge through the open-ended challenge and shared Makerspace environment alone. This approach allowed testing whether multidisciplinary collaboration could develop without mediation.

4.2.3 Observe - Iteration 1

4.2.3.1 Overview of Data Collected

During Iteration 1, data were collected from attendance records, organiser observation notes, informal student feedback, and four prototypes presented during Design Day. These sources provided insight into participation patterns and early collaboration dynamics.

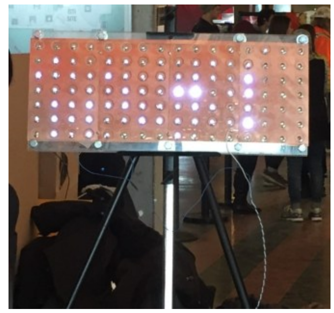
4.2.3.2 Artifacts Produced

On Design Day, four engineering teams presented the artifacts shown in Table 7. Team 1 presented *STEM Living Wall*, a three-actuator installation prototype that moved up and down in response to motion detected by sensors. The team envisioned a larger wall composed of multiple such components that would respond dynamically to movement in front of the installation. Team 2 presented *Painting with Light*, a copper plate incorporating a grid of LED lights that illuminated when a wet paintbrush passed over the surface. The system was activated through humidity sensors embedded in the plate. Team 3 presented *GG Upgrade*, a prototype plexiglass horse (GG) engraved with binary digits (0s and 1s) across its surface, transforming the object into a digital-inspired sculptural artifact. Team 4 presented *The Bike Bench*, a vintage bicycle installation in which the front wheel replaced one back leg of a bench, creating a functional sculpture.

Design Day judges identified Team 1's proposal—STEM Living Wall--as having the strongest potential for full implementation as an interactive art installation within the STEM building.

While creative, all artifacts reflected primarily engineering-driven approaches and did not demonstrate transdisciplinary integration.

Table 7 Iteration 1 Makerspace Challenge's Artifacts Submitted

Team 1 - STEM Living Wall 	Team 2 – Painting with light (Copper and Water) 
Team 3 – GG Upgrade 	Team 4 – The Bike Bench 

4.2.3.3 Observational Findings

Observation notes and informal feedback indicated strong enthusiasm among engineering participants but more reserved engagement from arts students. Although visual arts students attended the initial launch event, none joined the project teams.

The absence of multidisciplinary teams suggested that the collaboration central to the STEAM challenge did not materialise under minimal facilitation conditions. Without structured recruitment strategies or mechanisms to support interdisciplinary interaction, participation remained limited to engineering students and resulted in projects shaped primarily by engineering perspectives.

4.2.4 Reflect - Iteration 1

4.2.4.1 Key Insights

Recruitment and Epistemic Awareness

Reflection on Iteration 1 revealed that recruitment strategies were insufficient to engage students across disciplinary boundaries. A single launch event proved inadequate for sustaining participation from visual arts students, and the absence of continued outreach or facilitation limited participation to engineering students.

These challenges were compounded by disciplinary and spatial separation between the arts and engineering faculties, often described colloquially on campus as the "Great Continental Divide." Later student reflections confirmed the difficulty of navigating unfamiliar academic environments: *"As an artist, even being in the STEM building every Friday took some adapting, as we never have classes on 'the engineering' side of the campus" (I5 T2, female artist).*

Drawing on Gardiner's (2020) work on epistemic reflexivity (Section 2.5.2.1), the organising team recognised that disciplinary differences in learning cultures had not been adequately considered. Visual arts education typically emphasises individual exploration, whereas the Makerspace Challenge required team-based collaboration on externally defined problems. This misalignment likely discouraged participation.

Collaboration and Design Outcomes

The resulting prototypes reflected creative experimentation but remained primarily grounded in engineering approaches. Although several teams explored interactive installations, the absence of arts participation limited the diversity of perspectives informing the design process. As a result, projects largely emphasised technical functionality rather than the integration of artistic, conceptual, or experiential dimensions.

Pedagogical Implications

From a pedagogical perspective, Iteration 1 demonstrated that multidisciplinary collaboration does not emerge spontaneously in the absence of structured support. While engineering students showed strong enthusiasm for the challenge, additional scaffolding was required to bridge disciplinary cultures and encourage participation across faculties.

These observations raised important research questions regarding recruitment strategies, participation dynamics, and the forms of scaffolding required to support meaningful transdisciplinary collaboration.

These insights informed the design of the subsequent iteration, in which additional pedagogical scaffolding was introduced to support artistic engagement and collaborative design processes.

4.2.4.2 TD-SDT Evolution

Insights from Iteration 1 informed the initial development of the *Transdisciplinary STEAM Design Toolkit (TD-SDT)*. The absence of multidisciplinary teams highlighted the importance of recognising disciplinary epistemic cultures and designing recruitment strategies that account for these differences.

In particular, the iteration underscored the need for *epistemic awareness* when initiating cross-disciplinary collaborations. Recognising differences in disciplinary norms, learning practices, and institutional contexts became a foundational consideration in the evolving toolkit.

Table 8 summarises the first conceptual and pedagogical elements incorporated into the TD-SDT following this initial experiment.

Table 8 Evolution of the TD-SDT –After Iteration 1

TD-SDT Dimensions	Concept	Representative Tools / Practice	Iteration Introduced
Epistemic Reflexivity	Awareness of disciplinary assumptions	Discipline appropriate recruiting / scaffolding	1

4.2.4.3 Contribution of Iteration 1 - Recruitment and Epistemic Awareness

Iteration 1 revealed that multidisciplinary collaboration did not emerge spontaneously in the absence of intentional facilitation. The findings highlighted the importance of recognising epistemic differences between artistic and engineering practices and the need for discipline-sensitive recruitment strategies. These insights informed subsequent iterations, which introduced more structured approaches to support participation and collaboration across disciplines.

4.3 Iteration 2 - STEAM Course Integration (2018)

Building on insights from Iteration 1, the second iteration integrated a STEAM design challenge into the regular engineering curriculum. Whereas the first iteration relied on voluntary extracurricular participation, this iteration explored whether STEAM collaboration could be scaffolded within a structured course environment.

4.3.1 Plan - Iteration 2

4.3.1.1 STEAM Design Challenge and Research Focus

The *STEAM Design Challenge* remained the creation of interactive art installations for the new STEM building (see Section 4.2.1.1). However, instead of multidisciplinary student teams, engineering students collaborated with an external art client. The guiding questions therefore became:

- *Can engineering students meaningfully engage with artistic practices within an engineering design course?*
- *Can collaboration with an art client deepen engagement with artistic challenges in a single-discipline cohort?*

Students responded to a creative commission brief requiring engagement with artistic goals, client dialogue, and creative prototyping. This structure aligned with the familiar client-focused engineering design model (discussed in section 3.6.6), easing integration into the curriculum.

The *TD-SDT Research Focus* in this iteration examined whether existing engineering design tools could support STEAM design and inform development of the TD-SDT. Design thinking approaches were tested for their capacity to incorporate artistic practices.

Iteration 2 therefore focused on tools aimed at strengthening collaboration, artistic awareness, and reflexivity, including: the Stanford Design Thinking model and Double Diamond framework to structure iterative, human-centred problem framing and solving; the art-client-model to reframe client relationships toward co-creation and dialogue; artistic scaffolding tools such as curated inspirational art presentations, object-based enquiry, and studio-based critiques to support aesthetic cognition and alternative modes of inquiry; public exhibition through Design Day to foreground communication, narrative, and accountability; collaboration and reflexivity tools, including group contracts and ITP Metrics personality assessments, to surface team dynamics, support self-awareness, and foster epistemic humility. Together, these elements formed a more intentional scaffolding to support collaborative sensemaking and informed further TD-SDT development.

Key stakeholders included student teams, the teaching team, and the art client presenting the creative brief. The client contributed real-world artistic perspectives, while instructors scaffolded integration of artistic and technical goals.

4.3.1.2 Data Collection & Analysis Plan

Data collected included team final reports, client critiques, prototypes, final artifacts, and the researcher observation journal. Reports and observations provided evidence of how the introduced components influenced collaborative and design processes, while client critiques informed the iterative development of prototypes.

Artifacts were evaluated for artistic quality rather than disciplinary integration, as multidisciplinary collaboration had not yet occurred at this stage. Textual data were analysed using both inductive and deductive thematic analysis. The researcher observation journal was analysed using critical incident analysis (McAteer, 2013).

4.3.2 Act - Iteration 2

4.3.2.1 Implementation

Participants consisted of 38 first-year civil engineering students organised into eight teams within an established engineering design course (Described in Section 3.5). Lectures were delivered by engineering faculty, while laboratory activities were facilitated by technical staff.

Teams worked in classroom and Makerspace environments, engaging with the art client at four key moments during the semester: 1) Presentation of requirements and inspirational curated art references (week 2); 2) Concept critique with written client feedback (on 3 proposed concepts)(week 7); 3) Prototype review with oral critique (week 9); 4) Final presentation at Design Day (week 11). By the end of class, each team produced an interactive art installation prototype responding to the creative brief.

4.3.2.2 TD-SDT Components Studied

Iteration 2 introduced structured artistic, communication, and reflexive tools to address limitations identified in Iteration 1. The intervention was implemented within an existing engineering design course, whose validated curriculum (Section 3.5) served as the structural foundation for integrating STEAM objectives. This research selectively adapted and experimented with specific concepts and tools to explore their relevance to STEAM design and to inform the evolving TD-SDT.

Stanford Design Thinking model

The *Stanford Design Thinking model* (see Section 2.3.1) was adopted as a project management framework guiding the student teams' design process and was already institutionalised in engineering education (Razzouk & Shute, 2012; Rodier et al., 2019, 2021). Design Thinking provided a human-centred and iterative structure through which teams moved from understanding the art-client's needs to developing and refining design solutions.

Within this process, the *Double Diamond* model (Section 2.3.2) supported phases of divergence and convergence, enabling teams to first articulate a shared problem definition and subsequently generate and evaluate multiple solution concepts. Selected concepts were then prototyped and tested with the art-client and other stakeholders, with feedback informing iterative refinement of the proposed designs.

Art-Client Model

A deliberate modification to the traditional *client-model* (Section 3.6.6) was introduced through the adoption of an *art-client model*. Whereas conventional design thinking positions the client as the recipient of a design solution, the art-client-model reframed this relationship through an artistic lens that emphasised co-creation, dialogue, and mutual transformation. Students, positioned as artist–designers, were encouraged to engage with the art-client as creative collaborators and co-inquirers rather than service providers.

This relationship was supported through *artistic scaffolding tools*—including curated presentations of artworks, object-based enquiry, studio critiques and exhibition—expanding aesthetic and conceptual engagement. Public exhibition at Design Day extended communicative accountability beyond the classroom, requiring translation of technical and artistic intentions to broader audiences.

Artistic Scaffolding Tools

Curated presentations of artworks exposed students—all from engineering backgrounds—to a range of contemporary and historical art practices engaging with interactivity, embodiment, materiality, and public space. Rather than serving as models to replicate, the artworks functioned as experiential and cognitive reference points that supported aesthetic cognition by expanding perceptual awareness and enabling engagement with legitimate alternative modes of inquiry beyond propositional or technical reasoning.

This was complemented by *object-based enquiry*, an art-informed pedagogical strategy encouraging direct engagement with physical or conceptual objects as sites of investigation. Through close observation, manipulation, and discussion, students were prompted to attend to form, materiality, symbolism, and embodied experience. Object-based enquiry was used to slow early ideation, promote abductive reasoning, and foreground non-instrumental ways of knowing central to artistic practice.

Structured *critiques/feedback* were also introduced as a recurring reflective practice. Drawing from studio-based art education, critiques created a shared space for teams to present work-in-progress, articulate intentions, and receive constructive feedback from the art-client, as well as peers and instructors. These sessions emphasised dialogic exchange rather than evaluative judgment, supporting reflexivity, perspective-taking, and iterative refinement across disciplinary perspectives.

To extend the communicative and performative dimensions of the work beyond the classroom, projects were showcased during *Design Day, a juried public exhibition (Section 3.6.5)*. This public-facing event required teams to translate their design intentions and processes for a broader audience, reinforcing the importance of communication, narrative, and contextualisation in both artistic and engineering practices. The exhibition also served as a moment of accountability and validation, situating student work within a real-world institutional context.

Team Contract

In parallel, *communication tools* were introduced to support team coordination and collaboration. Notably, *group contracts* (Section 3.6.2) were implemented early in the iteration to prompt explicit discussion of roles, expectations, communication norms, and conflict resolution strategies. These contracts aimed to surface implicit assumptions and provide a shared reference point for managing collaboration over time.

Reflexivity Tools

Finally, *reflexivity tools* (Section 2.5.2.1) were integrated to support both *individual and collective self-awareness*. Students completed *ITP Metrics* (Section 3.6.1) personality assessments, which were used as reflective—rather than prescriptive—instruments to prompt discussion around working styles, strengths, potential tensions, and team dynamics. Facilitated discussions encouraged teams to recognise diversity in cognitive and interpersonal approaches, fostering epistemic humility and more intentional collaboration.

Together, these tools constituted a more intentional scaffolding of artistic practice, communication, and reflexivity in Iteration 2. This approach directly addressed the recruitment and collaboration challenges identified in the previous iteration and further informed the ongoing evolution of the TD-SDT.

4.3.3 Observe - Iteration 2

4.3.3.1 Overview of Data Collected

By the end of this iteration, data was collected from *eight teams composed of 35 students*, all from engineering (8 females and 27 males), as shown in Table 9. At this stage of the research, *individual reflective journals were not yet collected*, a practice that was introduced in later iterations. Team numbers are retained as originally assigned to maintain consistency across data sources.

Table 9 Iteration 2 Data Collected

Iteration 2 - Data Collected													
Identification								Individual Data		Team Data			Researcher Data
Iteration	Teams	N Students	A	E	O	F	M	Journals	Collated Journals	Final Reports	Prototypes	Final Artifacts	Journal
2	1	3	0	3	0	1	2			1	2	1	
	2	5	0	5	0	2	3			1	2	1	
	3	6	0	6	0	1	5			1	2	1	
	4	3	0	3	0	0	3			1	2	1	
	5	4	0	4	0	0	4			1	2	1	
	7	4	0	4	0	1	3			1	2	1	
	8	5	0	5	0	3	2			1	2	1	
	9	5	0	5	0	0	5			1	2	1	
2	8	35	0	35	0	8	27	0	0	8	16	8	1

Collected materials included: 8 final reports, 16 intermediary prototypes, 8 final artefacts, 8 art-client critiques, and 1 researcher observation journal. A summary description of the final artefacts is presented below, while a detailed description of prototype evolution and final artefacts can be found in APPENDIX P. Representative excerpts from final reports, art-client critiques, and researcher observation notes are discussed in the Observational Findings section.

4.3.3.2 Artifacts Produced

In iteration 2, eight engineering teams developed interactive art installations intended for the uOttawa STEAM building. as shown in Table 10. Together, these projects demonstrate how engineering students leveraged *interactivity, embodiment, and basic aesthetic strategies* to transform everyday actions—walking, touching, speaking, and playing—into sensory installation prototypes intended to foster creativity and social interaction within shared public spaces of the STEM building.

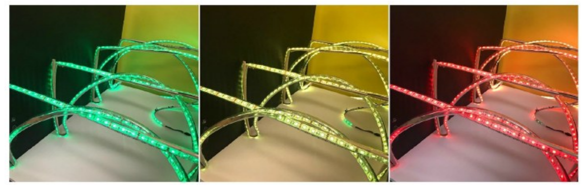
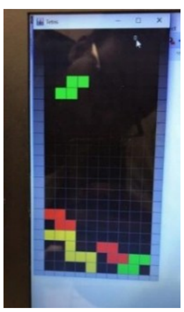
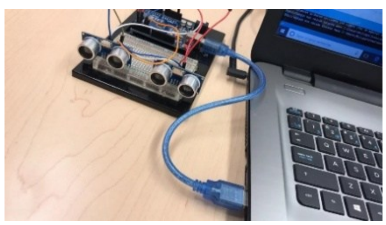
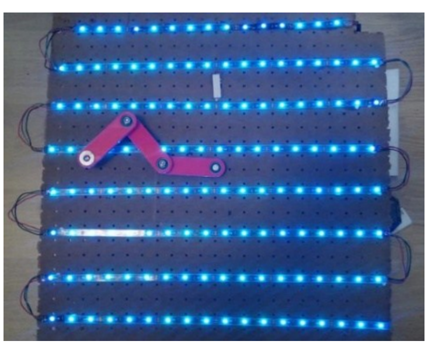
All teams successfully produced artifacts responding to the creative brief. However, while prototypes were technically competent, most prioritised *functional performance over aesthetic refinement*, a pattern consistent with projects developed within a single-discipline engineering context.

Table 10. Team 1 presented *Balls on the Wall* transforming a corridor into a playful passage where stepping on floor switches illuminated wall-mounted balloons. Team 2 presented *Ambiance*, an installation converting sound into a dynamic spectrum of shifting LED colours along a spiralled tunnel. Team 3 proposed *Interactive Screen Game*, inviting full-body movement to control falling shapes in a digital play environment. Team 4 developed *Musical Staircase*, converting a staircase into an instrument in which infinity mirrors illuminated and musical notes played when triggered by each step. Team 5 presented *Triple Pendulum Chaos*, visualising nonlinear physics through unpredictable kinetic motion and LED light trails. Team 7 proposed *Giant Interactive Piano*, allowing visitors to step on oversized keys to create music collaboratively. Team 8 developed '*Mouvement' DEL*, suspending spherical luminous forms overhead that awakened in response to nearby motion. And Team 9 proposed *Brain*, an installation using a touch-activated plasma sphere to animate glowing cable "synapses," linking human gesture to neural metaphor.

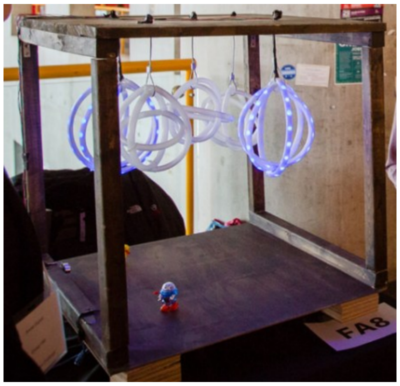
Together, these projects demonstrate how engineering students leveraged *interactivity, embodiment, and basic aesthetic strategies* to transform everyday actions—walking, touching, speaking, and playing—into sensory installation prototypes intended to foster creativity and social interaction within shared public spaces of the STEM building.

All teams successfully produced artifacts responding to the creative brief. However, while prototypes were technically competent, most prioritised *functional performance over aesthetic refinement*, a pattern consistent with projects developed within a single-discipline engineering context.

Table 10 Iteration 2 Teams Prototypes

Team 1 – P3 	Team 2 -P3 
Team 3 -P3  	Team 4 – P3 Musical Stairs 
Team 5 – P3 	Team 7 -P3 

Team 8 – P3



Team 9 – P3

4.3.3.3 Observational Findings

The eight final reports were analysed to identify evidence of the influence of tools introduced during this iteration on transdisciplinary collaboration (TD Process) and transdisciplinary knowledge creation (TD Integration).

Thematic Analysis

An *inductive thematic analysis* of the final reports identified recurring references to several tools introduced during the course, including design thinking, prototyping, and art-client feedback. Table 11 presents the number of quotes extracted for each tool category. Representative quotations used as evidence for interpretation are presented in the Reflect section (Section 4.3.4).

Table 11 Iteration 2 Number of Quotes Extracted

TD-SDT Component	Number of Quotes	Teams							
Concept	Tool	T1	T2	T3	T4	T5	T7	T8	T9	Total
Project Management	Design Thinking & Double Diamond	9	6	2	3	1	3	1	2	27
	Prototyping	7	6	6	6	6	4	5	4	44
Art-Client-Model	Critiques of Prototype	9	2	4	4	3	4	2	5	33
Art-Studio Pedagogies	OBE, Exhibit, Presentation	4	4	3	3	4	3	2	3	26
Epistemic Awareness	ITP Metrics - Personality Types	4	6	3	3	3	2	2	3	26
Mutual Learning	Team Contract	0	0	0	0	3	0	0	0	3
		33	24	18	19	20	16	12	17	159

Researcher's Observations

The researcher observation journal highlighted several challenges encountered during the iteration. Students often required more time than initially allocated to fully benefit from critique sessions. In response, the art-client provided written feedback to each team to ensure more detailed and actionable guidance.

Despite these efforts, several teams struggled to significantly improve the aesthetic quality of their prototypes. In some cases, such as *Team 9*, the final prototype reflected limited aesthetic development and fell short of the intended experiential impact.

Overall, the observations suggest that while structured feedback mechanisms improved communication and supported iterative refinement, *technical prototyping skills alone were insufficient to achieve strong aesthetic outcomes*. These insights indicated the need for stronger artistic scaffolding and earlier integration of aesthetic considerations within the design process.

Artifact Analysis

Analysis of the eight final artefacts revealed varying degrees of success in translating the art-client brief into engaging interactive installations.

Teams 1, 4, and 8 demonstrated the strongest potential for further development. Their projects combined interactive mechanisms with spatial or experiential qualities that could plausibly support future implementation within the STEM building. Their prototypes demonstrated promising attempts to connect user movement or presence with responsive visual or auditory effects, reflecting an emerging awareness of how interaction design can shape shared public experiences. While aesthetic refinement remained limited, these projects established conceptual foundations that could support further development and integration in subsequent iterations.

Teams 2 and 5 achieved moderate success. Their prototypes were technically competent and responded to aspects of the brief, yet they prioritised functional demonstration over experiential or aesthetic coherence. While the interaction mechanisms operated as intended, the installations lacked a clearly articulated conceptual or experiential identity. As a result, although these projects demonstrated solid engineering execution, they would require stronger artistic framing and spatial consideration to develop into compelling interactive art installations.

In contrast, Teams 3, 7, and 9 encountered difficulty translating technical functionality into meaningful interactive or aesthetic experiences. While their prototypes operated at a basic technical level, the resulting installations demonstrated limited engagement, conceptual clarity, and aesthetic development. In several cases, interaction appeared secondary to technical demonstration, producing artefacts that satisfied course requirements but did not convincingly address the artistic ambitions of the brief. Researcher observations further indicated that Team 9's final prototype exhibited minimal aesthetic progression across development stages.

Artifact analysis indicates that while engineering teams successfully produced functional interactive systems, aesthetic integration and experiential design remained uneven. These findings suggest that exposure to artistic references alone was insufficient to produce strong STEAM outcomes, reinforcing the need for deeper artistic engagement and multidisciplinary collaboration in later iterations.

4.3.4 Reflect - Iteration 2

4.3.4.1 Key Insights

Process Scaffolding Through Design Thinking

Student reports provided clear evidence that the design thinking process functioned as a shared structuring framework for the project. Several teams explicitly described their work as progressing through the canonical stages of empathy, definition, ideation, prototyping, and testing. As one team noted : *« Ce rapport porte sur l'entièreté des étapes du design thinking entrepris pour réaliser une œuvre d'art interactif… passant de l'empathie à la définition, des idées aux prototypes et finalement jusqu'aux essais » (I2 T1)*. Another report similarly stated that *« le projet était basé sur les étapes du design thinking… toutes ces étapes… seront présentées dans le contenu de ce rapport » (I2 T7)*. Empathy toward the art-client was repeatedly identified as a foundational step. One team wrote: *« après avoir empathisé avec la cliente, l'équipe a pu ressortir une liste de besoins énumérés par celle-ci » (I2 T7*). Together, these excerpts support the interpretation that design thinking operated as an effective *process scaffolding tool*, enabling teams to structure their design activities and communicate their work in a coherent manner.

Prototyping as Experiential Learning

Student reflections consistently framed prototyping as a mechanism for learning and uncertainty reduction. One team explained: *« l'objectif d'un prototypage est de réduire l'incertitude » (I2 T8)*. Another team described the prototype as a way: *« d'apprendre plusieurs choses à propos de la faisabilité de notre projet… et de prendre en considération plusieurs risques dont on ignorait l'existence » (I2 T4)*.

Prototypes were also understood as *preliminary exploration tools rather than finished artifacts*: *« ce prototype a pour objectif de démontrer la conception préliminaire de notre projet en utilisant des matériaux de base » (I2 T5)*.

These excerpts suggest that prototyping supported *abductive reasoning, experiential learning, and iterative refinement*, enabling teams to externalise ideas, test assumptions, and progressively stabilise their design decisions.

Prototype Feedback and Dialog

Prototype feedback sessions emerged as key moments of dialogue between engineering teams and the art client. In these exchanges, prototypes provided a shared reference point that helped students communicate design intentions, explain technical constraints, and receive feedback on artistic and experiential aspects of the project.

Students frequently described the prototype as their primary means of communicating ideas to the client. As one team explained:

« Ce prototype est notre moyen primordial de communication avec nos clients afin d'avoir leur rétroaction, tout en leur montrant, expliquant et simplifiant notre projet » (I2 T4).

Rather than serving only as a technical demonstration, the prototype functioned as a conversational interface through which ideas could be discussed and refined. Student reports indicate that client feedback played a formative role in shaping design decisions. One team noted:

« En ayant communiqué avec notre cliente, elle nous a dit que notre projet est original et intéressant » (I2 T7),

while another described how critique guided refinement of the concept:

« La cliente nous a donné son point de vue sur l'idée de conception et nous a orienté sur ce qu'elle aimerait avoir » (I2 T3).

In several cases, feedback directly prompted modifications to the proposed interaction:

« La cliente nous a proposé d'améliorer notre projet en y introduisant une interaction… plus intéressante et amusante que l'idée de départ » (I2 T3).

These observations suggest that prototypes helped mediate communication between artistic intentions and technical implementation. The shared discussion of prototypes enabled students and the client to negotiate design ideas despite differences in disciplinary expertise.

This dynamic anticipates mechanisms discussed in later iterations—such as boundary objects and interactional expertise—that support dialogue across disciplinary perspectives.

Limits of Artistic Scaffolding Without Multidisciplinary Teams

Although artistic tools—including curated art presentations, object-based enquiry, critiques, and exhibition—expanded students' aesthetic awareness, this increased awareness did not consistently translate into stronger aesthetic outcomes.

Many teams demonstrated improved sensitivity to experiential dimensions; however, final prototypes often remained *technically driven*, with aesthetic quality secondary to functional performance.

These results suggest that while artistic scaffolding enriched students' design processes, such tools alone could not substitute for the *epistemic and creative contributions that art students might bring when directly embedded within multidisciplinary teams*.

The excerpts suggest that the combined use of design thinking, prototyping, and client feedback supported structured learning during Iteration 2. Design thinking provided a shared process for approaching the project, while prototyping allowed teams to explore ideas through making and reduce uncertainty. Client feedback, facilitated through the art-client model, helped teams reflect on and refine their design intentions.

Although multidisciplinary integration remained limited at this stage, these mechanisms encouraged reflective, user-centred, and iterative design practices.

From a TD-SDT perspective, Iteration 2 highlights the importance of combining process-oriented scaffolding (design thinking and prototyping) with structured opportunities for dialogue and critique.

4.3.4.2 TD-SDT Evolution

Insights from Iteration 2 further expanded the *Transdisciplinary STEAM Design Toolkit (TD-SDT)* by introducing several tools aimed at structuring collaboration, supporting iterative design, and strengthening communication between teams and the art-client. Table 12 summarises the evolving configuration of the TD-SDT following this iteration.

Table 12 Evolution of the TD-SDT –After Iteration 2

TD-SDT Dimensions	Concept	Representative Tools / Practice	Iteration Introduced
Epistemic Reflexivity	Awareness of disciplinary assumptions	Discipline appropriate recruiting / scaffolding	1
		ITP Metrics – Personality Types	2
Mutual Learning	Transparency	Team Contract	2
Enabling Infrastructure	Project organisation	Design Thinking / Double-Diamond	2
		Client / art-client-model	2
		Iterative Prototyping	2
Art-Studio Pedagogies	Artistic inquiry methods	Object-Based Enquiry	2
		Critique (feedback)	2
		Exhibit of Artifacts.	2
Artistic Exposure	Artistic reference and inspiration	Curated art presentation	2

4.3.4.3 Contribution of Iteration 2 - Process Scaffolding and Dialogic Feedback

Iteration 2 demonstrated that structured design processes and dialogic feedback—through design thinking, prototyping, and art-client critique—supported iterative learning and reflective practice. However, artistic awareness alone did not produce deeper integration without multidisciplinary teams. These findings informed subsequent iterations designed to strengthen aesthetic development and enable direct collaboration between arts and engineering students.

4.4 Iteration 3 - STEAM Summer Internship (2018)

This section presents Iteration 3 of the action research project. Building on insights from the previous iterations, the research team selected two winning prototypes developed earlier: *STEM Living Wall* from Iteration 1 and *Infinity Mirror* from Iteration 2 (see Table 13). The objective was to refine these concepts through sustained collaboration between engineering and visual arts students to enhance their artistic, experiential, and technical qualities.

These two prototypes were therefore carried forward for further development and full-scale realisation. The opportunity was structured as a *paid STEAM summer internship*, enabling students to develop the first two student-created public artworks intended for permanent installation in the University of Ottawa's new STEM building.

Table 13 Winning Prototypes from Iterations 1 & 2

Iteration 1 Winning Artifact – STEM Living Wall	Iteration 2 Winning Artifact – Infinity Mirror
	

Table 13 presents the two prototypes carried forward from the previous iterations. These two interactive installation prototypes were selected for refinement and full-scale realisation. The opportunity was structured as a paid STEAM summer internship, enabling students to develop the first two student-created artworks intended for permanent installation in the University of Ottawa's new STEM building.

Iteration 3 as a turning point in the research

Iteration 3 marked a turning point in the action research process. While earlier iterations primarily explored recruitment strategies, process scaffolding, and art–engineering dialogue through prototype development, this internship created conditions for sustained multidisciplinary collaboration around the realisation of permanent installations. The extended duration, dedicated resources, and shared workspace provided a more stable environment in which to examine the relational and epistemic conditions required for deeper transdisciplinary knowledge creation.

As a result, this iteration offered a richer opportunity to observe how collaborative dynamics—including trust, equal footing, productive friction, and community support structures—shaped both the design process and the resulting artifacts.

4.4.1 Plan - Iteration 3

4.4.1.1 STEAM Design Challenge and Research Focus

STEAM Design Challenge: In this iteration, the design challenge extended the question explored in Iteration 1—whether engineering and visual arts students could collaborate within an extracurricular context. However, the focus shifted from prototype development to the realisation of two permanent interactive installations intended for the new STEM building.

The learning objective remained to provide students with an environment conducive to multidisciplinary collaboration and creative prototyping. In contrast to Iteration 1, however, the expected outcome involved the public presentation of fully functional interactive artworks rather than conceptual prototypes.

TD-SDT Research Focus: The research focus for the TD-SDT examined how engineering and visual arts students could collaborate effectively to co-create permanent interactive installations of high artistic and technical quality suitable for public exhibition. A second question explored whether artistic quality could be significantly enhanced through sustained multidisciplinary collaboration within a full-time summer internship context.

To support this iteration, the research team initially planned the introduction of two TD-SDT components: (1) a process-driven, student-centred approach and (2) a scaffolding support structure.

The process-driven approach aligned with the second STEAM principle identified by Carter et al. (2021), which emphasises learning environments that are student-centred, exploratory, holistic, and tolerant of uncertainty and failure. The research organising team also planned the presence of a scaffolding support structure capable of responding to emerging technical and conceptual needs.

During implementation, two additional dynamics—equal footing and productive friction—emerged as influential factors shaping collaboration and knowledge creation.

4.4.1.2 Data Collection & Analysis Plan

Because this internship operated as paid employment rather than a credited academic course, student work was not graded and no formal assignments or written reflections were collected. Data collection therefore focused primarily on project artifacts and process documentation.

The primary data sources consisted of intermediate prototypes and final installations, researcher observation notes, and semi-structured student interviews.

Artifacts were analysed as indicators of artistic quality and disciplinary integration, both of which served as measures of transdisciplinary knowledge creation.

Artistic quality was evaluated using *formal analysis*--an approach activating perceptual attention and analytical articulation to examine visual elements contributing to aesthetic experience (further explained in Section 3.9.2.1). While disciplinary integration was assessed using the *Transdisciplinary Integration Quality Scale (TIQS)* described in Section 5.2.3.1.

Observation notes were analysed using *critical incident analysis* (Section 3.9.1) to identify events that significantly influenced collaboration and learning trajectories.

Semi-structured interviews (APPENDIX N) were transcribed verbatim and analysed through *inductive thematic analysis* (Section 3.9.3), with particular attention to themes related to collaboration, disciplinary negotiation, and TD-SDT mechanisms.

4.4.2 Act - Iteration 3

4.4.2.1 Implementation

To address recruitment challenges encountered in Iteration 1, the research team collaborated closely with visual arts faculty and technical staff to recruit qualified arts students for the internship. This strategy proved successful: ten candidates were interviewed and four visual arts students were selected.

On the engineering side, members of the teams responsible for the winning prototypes agreed to continue their involvement. As a result, a multidisciplinary team of eight students (four engineering and four visual arts) was formed.

With support from the Director of Visual Arts, Lorraine Gilbert, and engineering leadership from Dr. Hanan Anis, a full-time STEAM internship ran from May to August 2018. Technical staff from both faculties provided additional support.

Students organised themselves into two teams—Surface Tension and Equilibrium—each responsible for transforming an earlier prototype into a refined, technically functional, and visually compelling artwork suitable for permanent public installation.

Students largely self-directed their creative and technical processes, while faculty and technical experts provided scaffolding to address emerging challenges.

Bi-weekly multidisciplinary critique sessions involved architects, public artists, facilities engineers, and technical specialists. Students also gained access to fabrication resources within both faculties (Rodier et al., 2021).

After four months of full-time work involving collaborative design, prototyping, fabrication, and installation, both projects were successfully completed and installed as part of the STEM building's official launch.

These installations became the first permanent public artworks produced by student teams at the University of Ottawa.

4.4.2.2 TD-SDT Components Studied

This iteration examines how planned TD-SDT components influenced transdisciplinary knowledge creation, while also revealing additional emergent components. The planned components included a *process-driven, student-centred approach* and a scaffolding support structure that evolved into a *community of practice*. Two additional factors—*equal footing and friction*—emerged as significant influences. The Formal Analysis tool is also described.

A Process-Driven, Student-Centred Approach

As planned, internship activities followed the STEAM principle of a process-driven, student-centred approach (Carter et al., 2021). No predefined curriculum was imposed; rather, students' explorations guided project direction, methods, and outcomes. Faculty ensured access to required expertise and resources as needs emerged.

A Scaffolding Community of Practice (CoP)

The extended duration of the internship enabled strong scaffolding support, which evolved into a functioning *community of practice (CoP)* (Lave & Wenger, 1991). Students received continuous support from technical staff, specialised faculty, architects, facilities engineers, professional artists, and manufacturing experts. Students accessed both engineering fabrication facilities and visual arts workshops, as well as professional manufacturing services. Dedicated workspace further supported collaboration.

Regular critique sessions brought together engineers, artists, architects, and technicians, exposing students simultaneously to technical and artistic perspectives. Notably, professionals also benefited from their project participation, and several long-term collaborations emerged. Over approximately five months, this network of participants formed a *STEAM community of practice* enabling students' simultaneous technical, artistic, and collaborative development.

Equal Footing

Because earlier prototypes had been developed solely by engineering students, initial team dynamics positioned engineers as conceptual leaders and artists as aesthetic contributors. Visual arts students initially deferred to engineering decisions, limiting conceptual development.

Friction

Friction emerged in both teams during the development process.

The Equilibrium team produced an early prototype satisfying both functional and aesthetic requirements while complying with building safety constraints. The team integrated multiple disciplinary perspectives during the development process. Following this stage, work focused primarily on refinement of the initial concept.

By contrast, the Surface Tension team encountered difficulties in early stages, producing multiple unsuccessful iterations. Emotional tensions increased between disciplinary subgroups, requiring additional facilitation. Communication challenges and differing communication styles contributed to conflict. Faculty facilitators encouraged students to articulate positions respectfully and engage constructively with disciplinary differences.

The team continued development through these challenges and proceeded toward an outcome.

Similar tensions later emerged within the Equilibrium team; however, members chose not to engage in confrontation and prioritised project completion. Both teams ultimately produced installations aligned with their initial prototypes while satisfying practical installation constraints

Formal Analysis

To support the evaluation of artistic quality within STEAM projects, formal analysis was introduced as a structured interpretive tool. This approach directs attention to perceptual and compositional features, enabling students and researchers to examine how visual and spatial elements contribute to aesthetic experience (see Section 3.9.2.1 for a detailed description).

Students applied formal analysis to examine installations in terms of form, materiality, scale, and interaction. This process supported the articulation of artistic decisions that might otherwise remain implicit. During the research analysis phase, formal analysis was also used to compare artifacts produced by different teams.

4.4.3 Observe - Iteration 3

4.4.3.1 Overview of Data Collected

By the end of this iteration, data was collected from 2 teams (Equilibrium (EQ) and Surface Tension (ST)) composed of a total of 11 students: 4 from arts, 6 from engineering, 1 from biology, 5 females and 6 males (see details in Table 14). The individual-level data sources consisted of one semi-structured interview. The teams presented 2 final reports, 5 intermediary prototypes and 2 final artifacts. And 1 researcher observations journal was collected. A detailed description of the prototype evolution and final artifacts is presented in the Artifacts Produced Section below.

Table 14 Iteration 3 Data Collected

Iteration 3 - Data Collected													
Identification								**Individual Data**		**Team Data**			**Researcher Data**
Iteration	Teams	N Students	A	E	O	F	M	Journals	Collated Journals	Final Reports	Prototypes	Final Artifacts	Journal
3	1	4	2	2	0	2	2	0	0	1	2	1	
	2	4+3	2	4	1	3	4	1*	0	1	3	1	
3	2	11	4	6	1	5	6	1*	0	2	5	2	1
								*semi-structured Interviews					

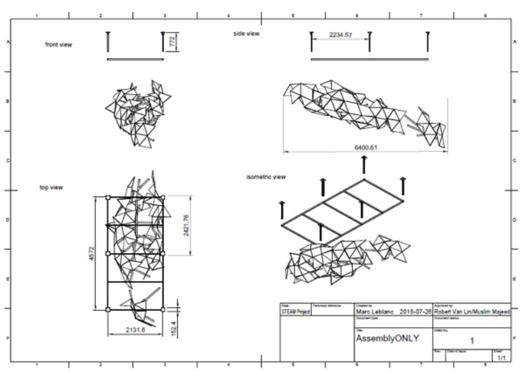
Based on the semi-structured interview and observation notes, three relational dynamics emerged as particularly salient across the internship: trust, epistemic friction, and how teams responded to conflict. The representative quotes extracted from the semi-structured interview and observation notes and critical researcher's observations notes are discussed in the Observational Findings section 4.3.3.3. And the intermediary prototypes and final artifacts collected are presented next.

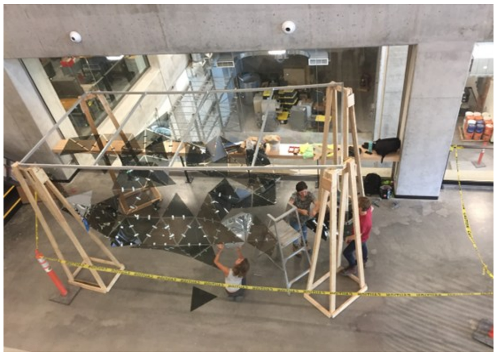
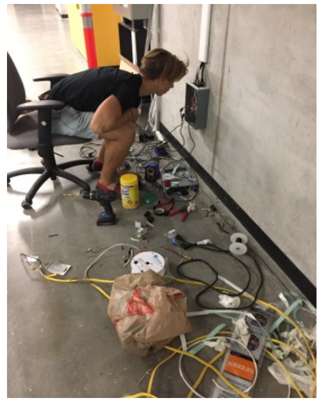
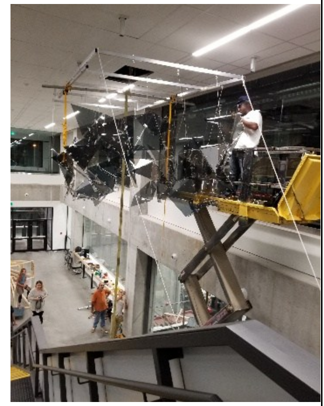
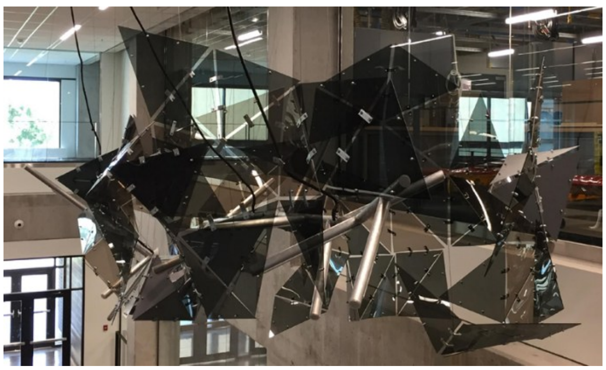
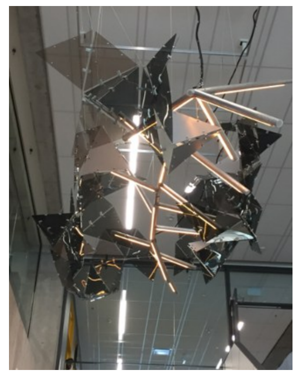
4.4.3.2 Artifacts Produced

Equilibrium - Artifacts Evolution

Table 15 below presents the evolution of the *Equilibrium* project through successive artifacts. The initial prototype (EQ–P0) corresponded to the final Iteration 2 prototype and served as the starting point for Iteration 3. Prototypes EQ–P1 through EQ–P3 document subsequent refinements. The “Installation” images document on-site construction, electronics installation and testing, and final suspension from the ceiling. “EQ–Final” shows the completed installation and “EQ–Final Video” presents a video of the interactive behaviour.

Table 15 Iteration 3 Equilibrium Evolution

EQ – P0 	EQ – P1 
EQ – P2 	EQ – P3 

<table>
<tr><td colspan="2">EQ – Installation
</td><td></td><td></td></tr>
<tr><td colspan="2">EQ – Final
photo: B. Findley

Plexiglass, aluminum, stainless steel, plastic, LED strips & electronic components.</td><td colspan="2">EQ – Final
</td></tr>
<tr><td colspan="4">EQ – Final Video : Video of Equilibrium Functionality</td></tr>
</table>

Equilibrium - Formal Description

Equilibrium (Table 15, EQ–Final) consisted of three integrated subsystems: (a) a ceiling-suspended illuminated sculptural element, (b) motion sensors integrated into the stair context, and (c) a concealed computer control system. The sensing and control elements blended into the architectural environment and remained minimally visible to users.

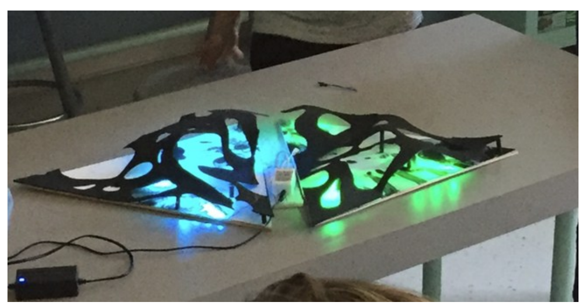
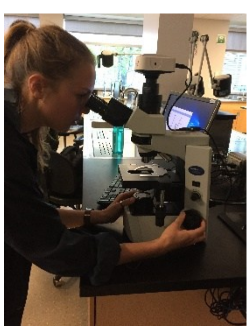
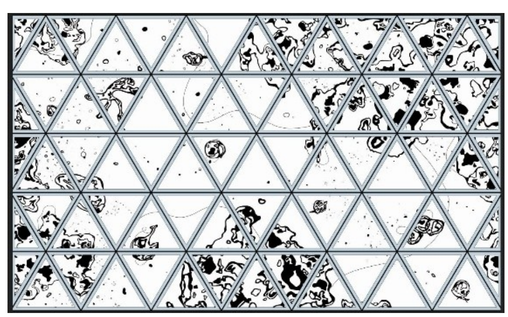
Visually, the suspended element was composed of translucent amber triangular plexiglass forms combined with reflective, mirror-like triangular surfaces. These units were arranged in cloud-like clusters around an aluminum branch-like structure. The composition was suspended from a rectangular aluminum frame using thin, minimally visible wires, creating the impression of floating forms. As visitors moved up or down the stairs, programmable LED segments illuminated sequentially in response to motion, producing a distributed light activation across the stairwell.

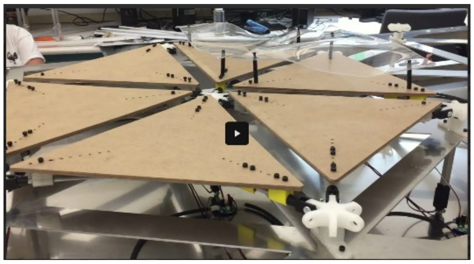
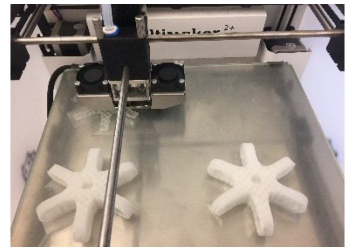
Conceptually, the installation's visual tension—between suspended geometric elements and the central tubular light structure—evoked a fragile equilibrium between opposing forces. The team used this balance as a metaphor for multidisciplinary coordination: artistic and engineering approaches interacted through iterative adjustments until the resulting structure satisfied both technical constraints and aesthetic intentions. Overall, Equilibrium complemented the building's minimalist industrial architecture while encouraging stair use through interactive illumination.

Surface Tension **- Artifacts Evolution**

Table 16 presents the evolution of the Surface Tension project through successive artifacts. The initial prototype (ST–P0) corresponded to the final Iteration 1 prototype and served as the starting point for Iteration 3. Prototypes ST–P1 through ST–P3 document subsequent revisions. The "Installation" images document on-site construction, component handling, and transport of the structure to its final location. "ST–Final" shows the completed installation and ST–Final Video : its interactive behaviour.

Table 16 Iteration 3 Surface Tension Evolution

ST – P0 	ST – P1 
ST – P2 	ST – P2 

ST-P3	ST – P3
	 

ST – Installation

ST – Final

photo: S. Hodgson
Aluminum, acrylic, plastic, ink, and electronic components

ST – Final Video : Video of Surface Tension functionality

Surface Tension - Formal Description

Surface Tension (Table 16, ST–Final) was an interactive installation composed of 75 triangular elements that responded to spectator movement. The installation comprised four core components: (a) three laser-cut aluminum frames, (b) 75 plexiglass and foam-core triangles actuated via pistons/actuators, (c) a concealed logic/control system, and (d) a camera-based sensing system mounted at the top of the structure. The hidden control system included an Arduino and a Raspberry Pi.

Each triangular unit layered two visual elements: a flat substrate laser-etched with imagery derived from microscopic aquatic microorganisms sampled from the nearby Ottawa River, and a wavy, aqua-tinted plexiglass layer. In motion, the wavy plexiglass produced a shimmering effect reminiscent of sunlight reflecting on water. The term surface tension—the cohesive force binding water molecules against external pressure—served as both a physical reference and a conceptual metaphor for cooperation, unity, and resilience.

The team began by collecting river water samples and documenting microorganisms through microscopy. These images were translated into stylised line drawings and integrated across the installation panels. The panels were interconnected and programmed to generate a coordinated undulating motion, evoking water flow. Raised acrylic elements complemented this effect by simulating shifting light across the surface of water.

4.4.3.3 Observational Findings

This section reports the analyses conducted on Iteration 3 data and links each claim to the underlying data sources and TD-SDT components involved. Across analyses, emphasis is placed on (a) the artifact outcomes as indicators of artistic quality and integration, and (b) process data (observations and interviews) as evidence of collaborative dynamics.

Thematic Analysis

An *inductive thematic analysis* of the final reports and interviews identified recurring references to several tools introduced during the internship, including student-centric process, equal footing, community of practice, trust, friction, ambiguity, communication, epistemic reflexivity. Table 17 presents the number of quotes extracted for each tool category. Representative quotations used as evidence for interpretation are presented in the Reflect section (Section 4.3.4).

Table 17 Iteration 3 Number of Quotes Extracted

TD-SDT Component	Teams		
Concept	T2 Eng	T2 Art	Total
Student-Centric Process	2	2	4
Equal Footing	7	7	14
CoP – Community of Practice	4	2	6
Trust	5	5	10
Friction	4	4	8
Ambiguity	2	4	6
Communication	2	2	4
Epistemic (Reflexivity/Empathy/Control)	2	2	4
	28	28	56

Researcher's Observations

The researcher observation journal highlighted the role of friction as a key dynamic shaping team outcomes during the iteration. Differences in disciplinary perspectives and working approaches generated tension within teams.

Teams responded to this friction in different ways. In *Equilibrium (EQ)*, tensions were largely avoided to maintain cohesion, resulting in steady progress but limited conceptual and aesthetic integration. In contrast, the *Surface Tension (ST)* team engaged directly with these moments of disagreement, using them to refine both the concept and its material realisation. This process was more demanding but supported deeper integration.

In parallel, the iteration fostered strong community-of-practice dynamics. The full-time internship context enabled sustained interaction, shared problem-solving, and ongoing exchange between students and professionals. This environment was observed to be both informative and intellectually stimulating, supporting mutual learning and a deeper understanding of collaborative processes.

Overall, the observations suggest that while sustained engagement supports collaboration, the way teams navigate friction significantly influences outcomes. Productively engaged friction contributed to deeper integration and marked an important condition for TD knowledge creation.

Artifact Comparative Formal Analysis – EQ and ST

This section applies a comparative formal analysis to the two interactive installations produced during the internship (Equilibrium and Surface Tension). As established in the methodology chapter (Section 3.9.2.1), formal analysis offers a systematic approach for assessing artistic qualities by examining how visual, material, spatial, and interactive elements function within the work. In this study, formal analysis was used to compare the artistic strength of each team's artifact. This comparison then informed interpretation in the Reflect section (Section 4.4.4) regarding how team dynamics—particularly the presence and navigation of friction—may have contributed to differences in output quality.

Comparative analysis indicated that Equilibrium achieved a coherent balance between architectural integration and user interaction within a constrained spatial context. Its suspended geometric composition echoed the STEM building's industrial-minimalist aesthetic, and its sensor-triggered LED activation offered clear, legible interaction aligned with stair movement. Conceptually, the work remained intentionally abstract: the metaphor of balance operated at a general level, emphasising harmony and coordination without a strongly grounded narrative anchor.

By contrast, *Surface Tension* integrated material research, narrative coherence, and mechanical complexity into a more conceptually unified experience. The installation's triangular modules combined aesthetic properties—light, translucency, and motion—with research-derived imagery based on ecological sampling of the Ottawa River. Interaction was therefore not only functional but semantically aligned with the installation's central metaphor of water dynamics and cohesion. This tighter coupling between concept, material, interaction, and narrative produced a more immersive and thematically grounded work.

Technically, Surface Tension also demonstrated greater system complexity through coordinated actuator-driven motion and integrated sensing/control infrastructure (Arduino and Raspberry Pi). Importantly, this complexity supported—not substituted for—conceptual integration: mechanical motion reinforced the metaphorical frame (flow, cohesion, pressure), strengthening the relationship between technological mechanism and artistic meaning.

Together, the two installations demonstrated distinct pathways for technology-art integration within STEAM practice: Equilibrium prioritised architectural harmony and clarity of interaction, while Surface Tension achieved a more research-driven, narratively integrated synthesis that supported broader reflection on ecology and interconnectedness.

TIQS Scoring of Artifacts – Discipline Integration

To assess the depth of disciplinary integration achieved in the two installations, the artifacts were evaluated using the *Transdisciplinary Integration Quality Score (TIQS).* Triangulation was applied across multiple indicators—including integration depth, novelty scores, and the evolution of disciplinary contributions throughout the prototyping process—to ensure the consistency and robustness of the assessment.

Across all three measures, the results converge on the same conclusion: *Surface Tension (ST)* demonstrates stronger performance than *Equilibrium (EQ)* in terms of disciplinary integration and conceptual development. The comparative analysis indicates that ST achieved a higher level of integration between artistic and engineering contributions, while also demonstrating greater conceptual novelty.

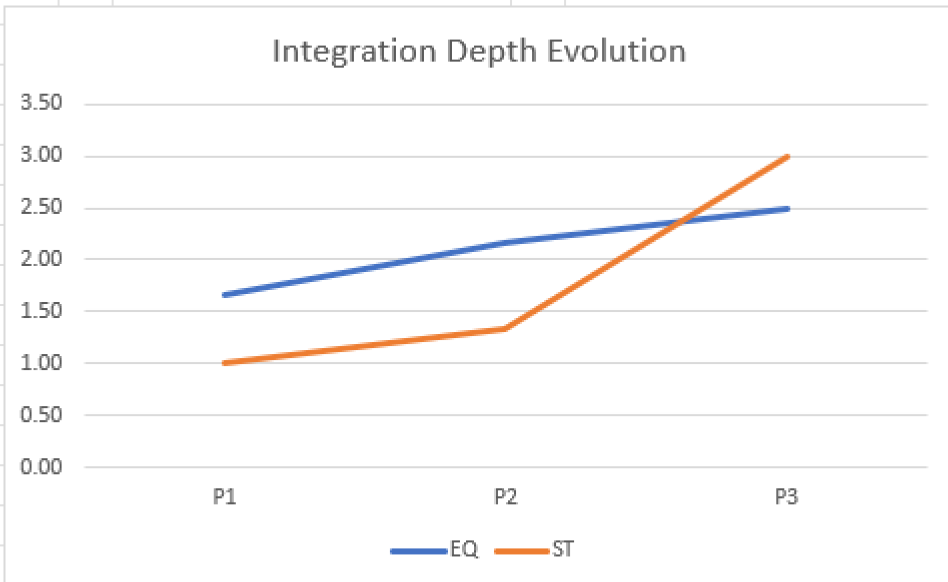


Figure 3 Iteration3 Integration Depth Comparison between EQ & ST

Figure 3 illustrates the comparison of *integration depth* between the two installations. The results indicate that ST achieved a more advanced level of disciplinary synthesis, despite a slower start, suggesting that artistic and technical elements were more fully interwoven in the final design.

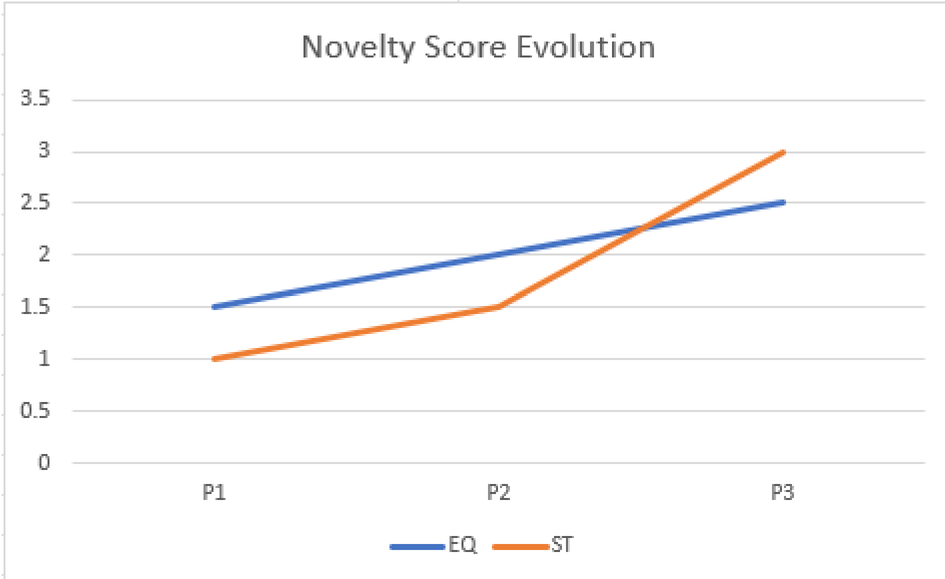


Figure 4 Iteration3 Novelty Score Comparison between EQ & ST

Figure 4 presents the *novelty score comparison*, further supporting this interpretation. The higher novelty score associated with ST suggests that the installation moved beyond incremental improvement between Prototype 2 & 3 to explore more transformative design possibilities emerging from the interaction between artistic and engineering perspectives.

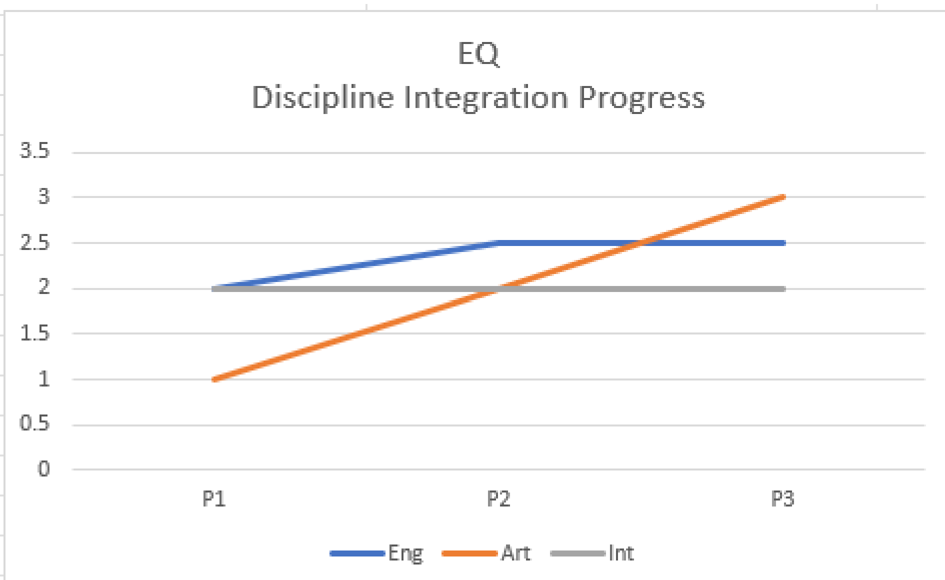


Figure 5 Iteration3 EQ Discipline Integration Progress Through Prototype Evolution

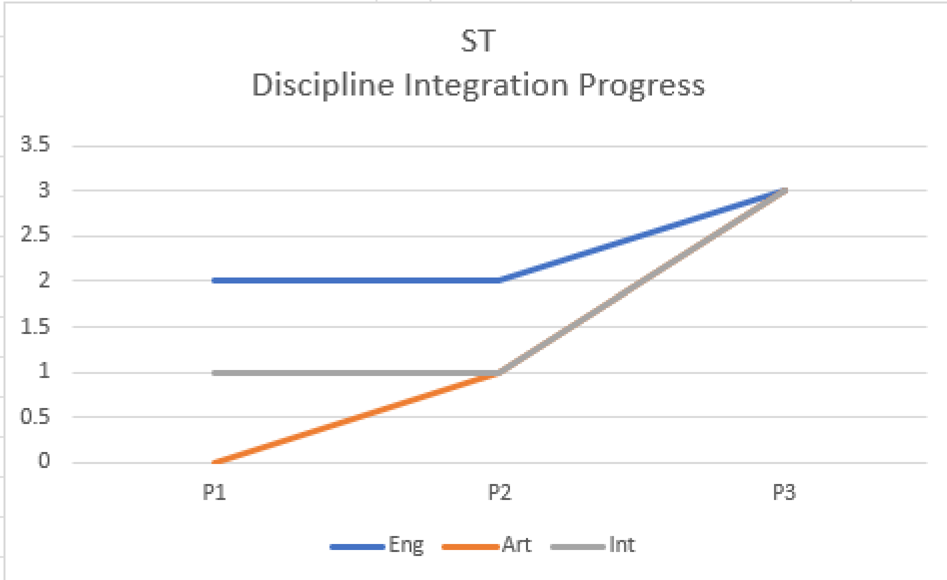


Figure 6 Iteration3 ST Discipline Integration Progress Through Prototype Evolution

Figures 5 and 6 examine the progression of disciplinary integration throughout the prototyping process for each artifact. The development trajectory of **EQ** shows a relatively uniform integration profile (grey line), with artistic and engineering contributions initially evolving in parallel. However, after Prototype 2 (P2), the engineering contribution plateaued while the artistic dimension continued a gradual progression toward Prototype 3 (P3). As a result, the integration profile remained largely stable, reflecting limited additional convergence between the two disciplinary contributions during the later stages of development.

In contrast, the development of **ST** reveals a different trajectory. Although the artistic contribution began at a lower initial level, it increased rapidly between P2 and P3. Meanwhile, the engineering and integration profiles started at higher levels and remained relatively stable through P2 before both increased again in the transition to P3. This pattern indicates earlier and more sustained interaction between disciplinary perspectives, allowing conceptual and technical elements to co-evolve throughout successive prototype iterations.

Taken together, these results suggest that the design process underlying ST facilitated deeper cross-disciplinary exchange and earlier integration of artistic and engineering perspectives. This trajectory contributed to a more cohesive final artifact and higher scores across all TIQS evaluation dimensions.

4.4.4 Reflect – Iteration 3

4.4.4.1 Key Insights

This section reflects on the relational and epistemic conditions that appeared to enable deeper transdisciplinary knowledge creation during Iteration 3, with particular attention to why *Surface Tension* emerged as the stronger outcome of the collaborative work.

Across the internship, teams deepened the use of *object-based inquiry* and *critical making* as central processes. Through material experimentation and iterative prototyping, students externalised emerging ideas into tangible forms—what Star & Griesemer (1989) describe as *boundary objects*—which then became shared reference points for dialogue, translation, and critique across disciplinary boundaries. As one engineering student described it, initially "starting from the tech," they evolved toward a synthesis where "everybody knew what everybody was talking about… and it was so smooth." *(I3 ST Eng Male)* The final artwork, *Surface Tension*, became a boundary object—a hybrid artifact that embodied both scientific and aesthetic logics. Their shared decision to "talk about science as a middle ground" and draw inspiration from the Ottawa River illustrates contextual emergence, where meaning coalesced through relational exploration rather than top-down design.

The internship environment therefore functioned as more than a production period; it became a relational and epistemic learning ecology in which collaboration, negotiation, and meaning making unfolded through shared practice.

To clarify the analytical structure of this reflection, the following subsections are organised in two movements. The first examines the enabling conditions that supported transdisciplinary collaboration during the internship, including the process-driven, student-centred approach, the development of equal footing among disciplines, the emergence of a community of practice, the establishment of trust, and the role of productive friction. The second movement provides an interpretive synthesis, examining how these relational conditions contributed to the emergence of ambiguity tolerance and epistemic reflexivity within the teams and helping explain why *Surface Tension* ultimately produced the stronger integrative outcome. Together, this progression traces an analytic arc from conditions of collaboration to their epistemic consequences, and finally to a comparative interpretation of the resulting artifacts.

Enabling Conditions:

Process-Driven, Student-Centred Conditions That Supported Transdisciplinary Emergence

The internship was intentionally structured around a *process-driven, student-centred* approach emphasising experimentation, uncertainty, and iterative learning (Carter et al., 2021). Rather than following a predetermined curriculum, students' evolving questions and needs shaped activities, tool use, and directions of inquiry. This openness created space for iterative sense-making and allowed artifacts to become both outcomes and instruments of thinking. Within this flexible structure, however, the internship also revealed that productive outcomes depended less on "having tools available" and more on whether teams cultivated relational conditions—particularly *equal footing, trust,* and *constructive engagement with friction*—that enabled those tools to function as integrative mechanisms rather than parallel contributions.

Equal Footing as a Precondition for Genuine Integration

A foundational condition for transdisciplinary collaboration was the development of *equal footing* between engineering and visual arts students. Because the original prototypes had been developed by engineers alone, the initial dynamic positioned engineers as concept owners and artists as aesthetic contributors. As one engineering student noted, the project was originally conceived as a *"technology project"* through the Makerspace Challenge, where the focus was on using "*motors and... frameworks to make it interactive*," rather than an art piece. This starting point meant that, initially, the engineers *"were not really thinking about what was the subject and what is the message that piece is trying to put across" (I3 ST Eng Male)*.

Early deference by art students—rooted in respect for the original designs—limited conceptual divergence and constrained the possibility of co-authored meaning. One engineer creator admitted being challenged by the need to negotiate his original vision for the prototype, *"I think coming into a project where we kind of came up with the concept, we had this sort of sense of 'this is our little baby'... things can change, it is not a big deal, you just need to just hang out" (I3 ST Eng Male)*. One art student reflected that art students often entered with apprehensions, observing, **"***We were worried about them not wanting to work with us because we're art students" (I3 EQ Art Female).* Another initially felt constrained by the technical focus, later admitting, *"I thought that the motion of the machine was enough to make it sculptural," (I3 ST Art Female)* but she eventually recognized the need to push beyond that initial box.

Over time, teams that explicitly renegotiated authorship and legitimacy were better able to shift from disciplinary service roles toward shared creative agency. This transition required difficult negotiation; one art student noted, *"We had to come to an agreement... I am so used to working on my own... and I had to ah give some room for other people" (I3 ST Art Female)*, *"There was just a little confusion. There just could have been some better communication I think at time… having different methodologies, just stressed both of us out a little bit." (I3 ST Art Female)*

This finding aligns with STEAM methodology literature that identifies equitable participation as a condition for successful collaboration (Carter et al., 2021). As this art student summarized, the eventual success stemmed from a shift in methodology: *"I think that this project worked so well cause we sort of met halfway and used both methodologies" (I3 ST Art Female)*.

Importantly, once parity was established, modifications to the original concepts were no longer perceived as "improvements" to someone else's idea but as collective design decisions, enabling the work to evolve beyond refinement toward deeper conceptual integration. By the end of the process, the team achieved a state where *"everybody knew what everybody was talking about. And it was so smooth" (I3 ST Eng Male)*. This integration allowed the project to move from purely functional to meaningful, as the engineers realized, *"You can make something that is cool or you can make something that is cool and says something" (I3 ST Eng Male)*.

These observations suggest that the emergence of equal footing functioned as a critical mechanism enabling genuine disciplinary negotiation rather than parallel contribution. Within the evolving TD-SDT framework, this dynamic corresponds to *epistemic humility*, which allowed participants to reconsider initial assumptions and collaboratively reshape the design concepts. This was best exemplified by this engineer's reflection on their daily debates: **"***after talking and going home... and coming back and saying 'no you're right'... that was a big learning experience" (I3 ST Eng Male)*. Ultimately, this humility allowed the team to see the project not as a rigid plan but as an evolving entity, with this art student concluding, *"It is important that when you're working in a group project, you do not get fixated, cause it is just going to go as it goes" (I3 ST Art Female)*.

Community of Practice as a Living Scaffolding System

Beyond the planned support network (mentors, architects, technicians, staff), a more organic *Community of Practice (CoP)* emerged through sustained collaboration and shared problem solving (Lave & Wenger, 1991). Within such communities, learning occurs through what Lave and Wenger describe as **legitimate peripheral participation**, a process in which newcomers gradually move from peripheral involvement toward fuller participation as they gain competence and confidence. In the internship context, students initially relied heavily on guidance from faculty, technicians, and professional collaborators. Over time, however, they increasingly contributed their own expertise and began supporting one another in solving technical and artistic challenges. This progressive shift illustrates how participation within the community enabled simultaneous development of technical skills, artistic sensibilities, and collaborative practices.

Rather than following a linear production pathway, the internship evolved as a living system: students identified what they needed to learn, sought expertise from one another and from professionals, and contributed to a shared pool of knowledge. Evidence of this learning ecology became visible as students began adopting elements of each other's disciplinary language, values, and criteria. One engineering student described a durable shift in perceptual orientation: *"Now in the back of my head, I'm always thinking: 'Does it look the way we want?'" (I3 ST Eng Male)* This comment suggests that prolonged co-participation did not merely add aesthetic "awareness," but reconfigured habitual evaluative attention—an indicator of integrative learning rather than surface exposure.

A second excerpt shows how artistic critique expanded the engineer's understanding of aesthetic value as meaning-bearing rather than decorative: *"So, when the artist said to me: 'all the art you see, it looks nice but if you really look into it, all the stuff that looks nice also says something really cool.' And the people that, you know, make these really cool things, that say something, this is, like, the important work that is kind of going on in the world and this is what we should be focusing on.' So, I think that was the big learning experience for me." (I3 ST Eng Male)*

These shifts support the interpretation that CoP functioned as an essential TD-SDT enabling condition in this iteration: it created a porous learning environment in which expertise circulated, critique became a shared practice, and disciplinary boundaries became sites of learning rather than fixed divisions.

These dynamics indicate that the internship environment operated as a community of practice, enabling knowledge circulation across disciplinary and professional boundaries. Within the TD-SDT framework, the community of practice therefore functioned as a *mutual learning infrastructure*, supporting the integration of technical and artistic expertise.

Trust as the Stabilising Condition for Risk-Taking and Vulnerability

Across teams, *trust* emerged early as a stabilising relational condition that enabled collaboration under uncertainty. Students entered the internship with apprehensions rooted in disciplinary stereotypes—art students feared rejection or devaluation, and engineering students anticipated communication breakdowns. *"We were worried about them not wanting to work with us because we're art students." (I3 EQ Art Female)* , *"I heard things about engineers being difficult to work with… But that ended up not being the problem after all…" (I3 ST Art Female)* As hands-on work progressed, trust was built incrementally through repeated interactions, shared problem solving, and the experience of being taken seriously by collaborators. One art student summarised this relational shift succinctly: *"I think it was more about getting to know each other and having this trust that made it happen." (I3 ST Art Female)*

As trust grew, students reported increased candor and emotional safety in communication. An engineering student described the emergence of direct, reality-based exchanges: *"Now, we have the relationship where I can tell her that things are not going well. This is just the reality, and I am doing as best as I can, this is what is going on." (I3 ST Eng Male)* Trust also expanded inward, supporting self-efficacy in uncertain contexts: *"I think trusting myself, was another big thing, I could tell myself. … we are smart, we can do it, just trust yourself." (I3 ST Eng Male)*

Importantly, students' reflections suggest that trust enabled not only smoother teamwork but longer-term identity and trajectory shifts. One participant linked increased confidence to new opportunities and a broadened sense of future possibility: *"This whole experience made me so much more confident. And I think, at least in this program, I got so many more opportunities. I am sort of the person that is giving the tours now, and I am making way more connections. I got a job working at Makerspace, which is just like incredible — I am having so much fun. And I think it is just helping me keep an open mind about everything I am going to be doing in the future. I am not planning on going on one path anymore — so, yah!" (I3 ST Art Female)*

Similarly, an engineering student described a durable reorientation toward hybrid professional identity: *"After working on this project,… Ah, but even the way that I think about the work that I am going to be doing in the future, I want it to be influenced by art and design — have that sort of angle to it. I am not looking to do regimented, strictly engineering work anymore." (I3 ST Eng Male)*

These accounts suggest that trust functioned not only as a team dynamic but as a condition for epistemic and personal transformation—supporting the TD-SDT claim that carefully scaffolded transdisciplinary collaboration can expand both knowledge-making and identity horizons.

Moreover, these accounts also suggest that trust functioned as a stabilising relational mechanism that enabled students to engage in vulnerability, critique, and experimentation. Within the evolving TD-SDT framework, trust therefore operated as a foundational condition allowing productive friction and epistemic negotiation to occur.

Friction as a Generative Condition—When Addressed Rather Than Avoided

While trust provided stability, *friction* provided generative disruption. Task and opinion conflicts arose frequently as students negotiated differing disciplinary languages, value systems, and methodological commitments. In Surface Tension, these tensions often operated as *productive epistemic friction*—moments that slowed down decision-making, surfaced assumptions, and compelled teams to reframe problems from multiple perspectives. The comparative analysis already suggests that Surface Tension achieved greater conceptual and technical integration; the process data further indicates that this was not despite conflict, but partly because conflict was engaged as a design resource.

Student interviews explicitly support the claim that negotiating difference required active concession, shared authorship, and communicative work. One art student described the difficulty of making space for co-authorship: *"We had to come to an agreement as well. Also, which is also very difficult. Ah, I am so used to working on my own and I have the concept, I have the idea, and I had to ah give some room for other people." (I3 ST Art Female)*

Another excerpt highlights how divergent methodologies produced strain: *"There was just a little confusion. There just could have been some better communication I think at time… having different methodologies, just stressed both of us out a little bit." (I3 ST Art Female)*

And the engineer's quote illustrates the epistemic work required to translate disciplinary vocabulary and integrate new conceptual tools: *"At the beginning, there was words that she was using that I just didn't understand. … Like 'Motif' was one of them. … But then after talking and going home and being able to think about it … that was a big learning experience." (I3 ST Eng Male)*

These accounts align with Stengers' argument that friction, hesitation, and preserved difference are not obstacles to be removed but conditions for transdisciplinary creativity (Stengers, 2011, 2018). In this iteration, Surface Tension's friction appeared to function as an "obligation to slow down," enabling participants to remain responsive to each other's demands rather than defaulting to disciplinary dominance or premature closure (Stengers, 2018).

Crucially, the internship also showed that friction did not automatically become productive. The decision to address or avoid conflict strongly shaped collaborative depth. Teams that named tensions, tolerated discomfort, and negotiated differences directly developed greater adaptive capacity than teams that minimised conflict to ensure completion. Friction operated as a fork in the road: addressed friction supported learning and integration; avoided friction stabilised production but limited conceptual expansion.

These observations suggest that friction functioned as a generative mechanism that slowed decision-making and surfaced disciplinary assumptions. Within the TD-SDT framework, such *productive friction* created opportunities for deeper epistemic negotiation and integration.

Together, these relational conditions shaped not only how teams collaborated but also how participants negotiated disciplinary differences and integrated distinct ways of knowing. The following sections examine how these dynamics contributed to the emergence of ambiguity tolerance and epistemic reflexivity within the teams' design processes.

Interpretive Synthesis:

Ambiguity Tolerance and Epistemic Reflexivity: Integrating "Why" and "How to"

A further outcome of friction and sustained collaboration was the emergence of *ambiguity tolerance and epistemic reflexivity*—the capacity to reflect not only on the project content but on ways of knowing. Engineering students accustomed to clear metrics initially expressed discomfort with open-ended artistic iteration, while art students were initially challenged by technical precision and constrained timelines. Over time, both groups adapted. One engineering student articulated a shift away from purely technical success criteria toward meaning making: *"We can make something that looks cool and that kind 'a feels cool, but if it does not say something and does not like give a message, then it is just something that looks cool." (I3 ST Eng Male)*

An art student described the affective discipline of remaining open under uncertainty: *"Just keep an open mind. Try to relax. Cause everything just falls into place." (I3 ST Art Female)*

More specifically, students began to identify a patterned epistemic difference: art students were more likely to prioritise the **"***why***"** (conceptual thesis, message, meaning), while engineering students prioritised the **"***how to***"** (mechanism, feasibility, iteration-by-testing). The engineer's reflection captures how this distinction became visible only through the collaboration:
"So, initially when we were working on the prototype for the design show, we were not really thinking about what the subject was and what is the message that the piece is trying to put across. So, after we won the competition, and we started to work on it in the summer, we were working with artists — they said, 'eh guys, we can make something that looks cool and that kind of feels cool, but if it does not say something and does not like give a message, then it is just something that looks cool.'" (I3 ST Eng Male)

The art student's description provides a complementary explanation of methodological difference and the eventual "meeting halfway" that enabled integration: *"We definitely had different ways of thinking. I think when I go into something I look at — when I am making art, at least, I kind of work in an essay format. I figure out what the thesis is, the concept, then I start doing research to make that happen. Whereas, I think the engineers, they start off with maybe the idea and prototype it and keep prototyping it and working on it. And they are not fixated on what this overall idea might be, they just kind of let it happen. And I think that this project worked so well because we sort of met halfway and used both methodologies." (I3 ST Art Female)*

These paired accounts show epistemic negotiation in action: successful teams did not erase disciplinary differences but learned to hold them together—integrating iterative prototyping with conceptual development. This blending created conditions for novel insights and reinforced the importance of explicitly designing learning environments that support epistemic negotiation and reflexive awareness.

These epistemic shifts influenced how teams approached design decisions and conceptual development. The comparative outcomes of the two installations therefore provide insight into how differing collaborative dynamics shaped the depth of integration achieved.

Why Surface Tension Became the Stronger Output

Synthesising across observations, interviews, and comparative artifact analysis, Surface Tension appeared to become the stronger overall outcome because the team more consistently enacted the relational and epistemic conditions required for transdisciplinary emergence. The team engaged friction rather than bypassing it, developed equal footing through negotiated authorship, leveraged the community of practice as a learning infrastructure, and cultivated trust sufficient to sustain vulnerability, disagreement, and iterative exploration. The result was not only a more conceptually integrated and technically complex installation, but also evidence of deeper perspective transformation among participants.

Overall, Iteration 3 refined the TD-SDT by demonstrating that frameworks and tools were necessary but insufficient on their own. What enabled transdisciplinary knowledge creation was a constellation of supports—social, procedural, and ethical—that activated students' epistemic agency. Trust enabled friction to become learning; reflection clarified disciplinary logics; the community of practice provided scaffolding; and through these dynamics, transdisciplinary knowledge became possible. Surface Tension exemplified how arts-integrated design can catalyse epistemic transformation—where knowing, making, and relating become inseparable processes of discovery.

4.4.4.2 TD-SDT Evolution

Iteration 3 marked a significant maturation point in the development of the TD-SDT by demonstrating that transdisciplinary knowledge creation depended less on the presence of individual tools than on the cultivation of relational and epistemic conditions that enabled integration to occur (Table 18).

This iteration confirmed the importance of equal footing, trust, productive friction, community of practice, and epistemic reflexivity as operational dimensions of the framework, while also refining earlier assumptions by showing that mutual respect alone does not guarantee integration and that aesthetic evaluation must be supported by conceptual development scaffolds. The internship validated discipline-aware recruitment, personality-informed team preparation, and structured support for navigating tension as necessary enabling conditions and positioned boundary-object–driven making as a central mechanism for interdisciplinary translation.

Importantly, the iteration established a benchmark for assessing whether similar TD dynamics can emerge under tighter curricular constraints, a hypothesis explored next in Iteration 4.

Table 18 Evolution of the TD-SDT After Iteration 3

TD-SDT Dimensions	Concept	Representative Tools / Practice	Iteration Introduced
Ambiguity	Tolerance for uncertainty	Open challenge: with few constraints (helps creativity)	3
Trust	Psychological safety for collaboration	Safe-space creation - create & protect safe-space for vulnerability	3
		Informal team building (shared meals, games)	3
		Team-level decision making	3
Epistemic Reflexivity	Awareness of disciplinary assumptions	Discipline appropriate recruiting / scaffolding	1
		ITP Metrics – Personality Types	2
		Recognition of epistemic differences (artists focus on *Why*, engineers focus on *How*)	3
Epistemic Humility	Equal participation across disciplines	Equal Footing in collaboration	3
		Stereotype deconstruction	3
Epistemic Friction	Productive negotiation of difference	Productive friction, and slowing decision process	3
Mutual Learning	Community-based knowledge exchange	Community of Practice	3
		Process-driven approach	3
		Student-centred approach	3
		Team Contract	2-3
Epistemic Boundary Mediation	Boundary Object	Prototypes, shared lexicon, collaborative artifact	3
Enabling Infrastructu re	Project organisation	Design Thinking / Double-Diamond	2-3
		Client / art-client-model	2-3
		Iterative Prototyping	2-3
Art-Studio Pedagogies	Artistic inquiry methods	Object-Based Enquiry	2-3
		Critique (feedback)	2-3
		Exhibit of Artifacts.	2-3
Artistic Exposure	Artistic reference and inspiration	Curated art presentation	2-3
		Artist Talk	3

4.4.4.3 Contribution of Iteration 3 - Relational Conditions for Integration

Iteration 3 demonstrated that deeper transdisciplinary knowledge creation depended on relational and epistemic conditions including equal footing, trust, productive friction, and community of practice. These conditions enabled meaningful negotiation across disciplinary perspectives and supported the integration of artistic and technical approaches. The iteration therefore marked a significant step in the articulation of the relational mechanisms underpinning the TD-SDT.

4.5 Iteration 4 – Recycling A STEAM Arranged Marriage (2019)

This section presents Iteration 4 of the action research project. Encouraged by the outcomes of Iteration 3, the research team piloted STEAM experience within a regular academic setting by bringing together an engineering design course and a visual arts sculpture course. The objective was to examine whether the transdisciplinary dynamics observed in the internship context could be reproduced within the constraints of a standard semester course.

Iteration 4 therefore represented a validation cycle testing whether the relational and epistemic conditions identified during the internship could be reproduced within the tighter temporal and institutional constraints of a regular academic course.

4.5.1 Plan - Iteration 4

4.5.1.1 STEAM Design Challenge and Research Focus

STEAM Design Challenge: In this iteration, the design challenge was framed around the following questions: Could engineering and visual arts students effectively collaborate within a shared course structure to co-create kinetic sculptures using recycled materials? And could a combined art–engineering course foster both artistic and technical excellence within a standard 12-week STEAM educational context?

TD-SDT Research Focus: The research objective of this iteration was to consolidate insights developed in previous cycles and test whether the transdisciplinary knowledge creation achieved in Iteration 3 could be reproduced using the TD-SDT developed thus far. For this reason, Iteration 4 did not introduce new TD-SDT concepts or tools; instead, it evaluated the effectiveness of the existing framework within a multidisciplinary classroom setting.

Accordingly, the guiding research questions were: Can transdisciplinary knowledge creation be achieved within a 12-week classroom composed of engineering and visual arts students? And can the current TD-SDT framework be productively leveraged to support TD knowledge creation under regular course conditions?

4.5.1.2 Data Collection & Analysis Plan

In this iteration, student experiences were collected through semi-structured interviews (see questions in APPENDIX E). Interviews were transcribed verbatim and analysed using inductive thematic analysis (Section 3.9.3) to identify emerging themes and representative quotations indicating the influence of TD-SDT components on transdisciplinary collaboration and knowledge creation.

Artifacts, including intermediate prototypes and final installations, along with researcher observation notes were collected to document process development and student learning trajectories. Additional text-based data sources, including student reflective journals and final reports, provided evidence of collaborative processes and integration dynamics.

Artifacts were assessed for both artistic quality and multidisciplinary integration as indicators of TD knowledge creation. Formal analysis methods (Section 3.9.2.1) were used to evaluate artistic qualities of final installations, while the *Transdisciplinary Integration Quality Scale (TIQS)* (described in Section 5.2.3.1) was applied to evaluate the level of disciplinary integration achieved. Together, these analyses supported assessment of the influence of TD-SDT components used in this iteration.

Text-based data were analysed using both deductive and inductive thematic analysis approaches (Section 3.9.3). Artifacts and prototypes—typically three to four iterations per team—provided additional evidence of integration depth across project development stages.

Finally, the researcher's journal, containing observational and reflective notes, was analysed using critical incident analysis (Section 3.9.1) to identify moments that marked significant shifts in team understanding or collaboration dynamics.

4.5.2 Act - Iteration 4

4.5.2.1 Implementation

In this iteration, the STEAM design experience combined the studio component of a second-year sculpture course with the laboratory component of a first-year engineering design course. While lectures remained discipline-specific—visual arts students studied contemporary art theory and sculptural practice, and engineering students focused on design thinking, project management, and team dynamics—all students met weekly in mixed-discipline teams for a three-hour joint studio–lab session. These sessions functioned as shared spaces for experimentation, fabrication, and interdisciplinary dialogue.

The central design brief tasked teams with creating kinetic sculptures constructed exclusively from recycled materials. The course partnered with *Recycl'ART,* a local recycled-materials art festival that served as both art-client and stakeholder, with selected works intended for public exhibition during the summer.

Over the 12-week semester, engineering and visual arts students collaborated in multidisciplinary teams to design and fabricate their sculptures. Through regular consultations with Recycl'ART representatives and instructional staff, teams iteratively refined their prototypes in response to stakeholder feedback and peer critique. The resulting artifacts are presented in the Data Collection section below.

4.5.2.2 TD-SDT Components

In alignment with the research objective of this iteration—to consolidate insights developed in previous cycles and test whether the transdisciplinary knowledge creation achieved in Iteration 3 could be reproduced within a standard academic course—no new TD-SDT concepts or tools were introduced. Instead, this iteration evaluated the effectiveness of the existing TD-SDT framework within a multidisciplinary classroom setting.

Accordingly, several previously established TD-SDT components were mobilised in this course context. These include object-based inquiry and critical making, which enabled teams to externalise ideas through material experimentation and shared fabrication processes; iterative prototyping, supporting cycles of testing and refinement; and authentic assessment through public exhibition, which provided external accountability and reinforced the communicative and experiential dimensions of the projects.

Additional components previously identified as critical—including equal footing between disciplines, collaborative negotiation supported by team contracts and facilitation, and community-of-practice dynamics emerging through sustained interaction—were likewise enacted through the course structure. Process-driven and student-centred pedagogical conditions encouraged teams to navigate uncertainty, negotiate disciplinary differences, and collectively shape project outcomes.

Together, this iteration functioned as a validation cycle for the TD-SDT, examining whether the combination of these established components could again support transdisciplinary collaboration and knowledge creation under the tighter temporal and institutional constraints of a 12-week course format.

4.5.3 Observe - Iteration 4

4.5.3.1 Overview Data Collected

By the end of this iteration, data was collected from seven teams composed of a total of 31 students: 15 from arts, 16 from engineering, 16 females and 15 males (see details in Table 19). Collected materials included: 7 final reports, 14 intermediary prototypes and 6 final artifacts and 1 researcher observations journal. A summary description of the final artifacts is presented below, while a detailed description of the prototype evolution and final artifacts can be found in APPENDIX R.

Table 19 Iteration 4 Data Collected

Iteration 4 - Data Collected														
Identification								Individual Data		Team Data			Researcher Data
Iteration	Teams	N Students	A	E	O	F	M	Journals	Collated Journals	Final Reports	Prototypes	Final Artifacts	Journal
4	6	4	2	2	0	1	3			1	2	1	
	7	4	2	3	0	3	2			1	3	0	
	8	4	2	3	0	3	2			1	1	1	
	10	5	2	2	0	2	2			1	2	1	
	11	4	2	2	0	2	2			1	2	1	
	12	5	2	2	0	2	2			1	2	1	
	14	5	3	2	0	3	2			1	2	1	
4	7	31	15	16	0	16	15	0	0	7	14	6	1

The representative quotes for textual data collected (student reflective journals and final reports), and critical researcher`s observations notes are discussed in the Observational Findings section 4.5.3.3. And a summary of the final artifacts collected is presented next.

4.5.3.2 Artifacts Produced

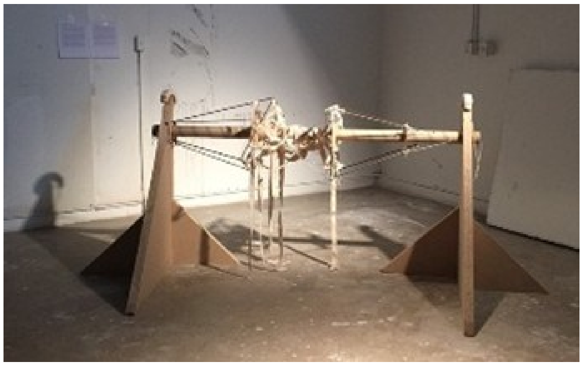
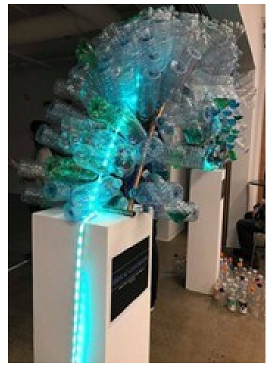
In Iteration 4, seven multidisciplinary teams developed kinetic sculptures using recycled materials for exhibition at the Recycl'ART festival (summarised in Table 20).

Projects explored themes of environmental sustainability, human interaction, and technological mediation through kinetic motion and audience engagement. Examples included *Digital Entanglement* (sound-based interactive installation), *Distorted View* (kinetic reflective sculpture altering perception), and *Wave of Consciousness* (interactive piece addressing ocean plastic pollution).

Collectively, these projects demonstrated that, when supported by TD-SDT scaffolding, multidisciplinary teams can successfully co-create interactive public artworks within a standard academic course that integrate technical functionality, artistic expression, and socially meaningful themes.

Table 20 Iteration 4 Teams Final Artifacts

Team 6 - Digital Entanglement 	Team 7 – Distorted View 
Team 8 – Impact 	Team 10 – Fallen 

Team 11 - Vortex 	Team 12 – Wave of Consciousness 
Team 14 – Orbital Simplicity 	

4.5.3.3 Observational Findings

Transdisciplinary Integration Quality Score (TIQS)

To assess the quality of disciplinary integration achieved during Iteration 4, the artifacts were evaluated using the Transdisciplinary Integration Quality Score (TIQS) framework. Triangulation was applied across three complementary indicators—integration depth**,** novelty scores, and disciplinary integration progress throughout prototype development—to ensure the coherence and robustness of the assessment. All teams in iteration 4 demonstrate an improved integration between Prototype 2 and prototype 3.

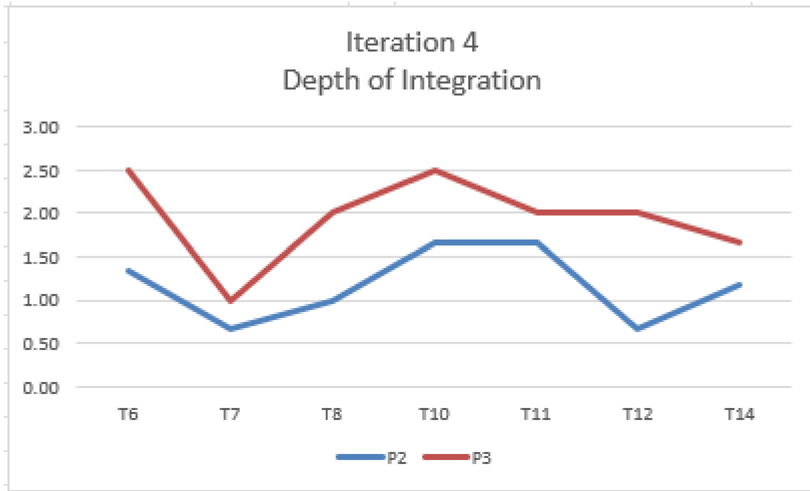


Figure 7 Iteration 4 Depth of Iteration All Teams

Figure 7 presents the overall depth of integration across all teams during Iteration 4**,** illustrating how disciplinary contributions evolved through the design process

4.5.4 Reflect - Iteration 4

The reflective analysis revealed several relational and epistemic conditions that supported transdisciplinary collaboration within the course environment. These included the emergence of communities of practice, the development of epistemic reflexivity across disciplines, and the cultivation of epistemic empathy among participants.

4.5.4.1 Key Insights

Iteration 4 demonstrated that meaningful transdisciplinary collaboration cannot be achieved simply by co-locating students from different disciplines or synchronising course schedules. Rather, it requires the deliberate creation of shared epistemic foundations and environments that support emotional and intellectual risk-taking. Teams that confronted rather than avoided conflict produced stronger collaborative outcomes, reinforcing Stengers (2018) argument that friction is not an obstacle but a productive condition for innovation. Public engagement through the Recycl'ART exhibition further reinforced the social relevance of student work and acted as a powerful motivational driver, giving projects real-world stakes and cultural visibility.

From a theoretical perspective, the iteration reinforced constructivist insights that learner-driven knowledge construction thrives in environments where experimentation, failure, reflection, and iteration are permitted. A systems perspective also became evident: student dynamics, course structures, institutional constraints, material availability, and stakeholder expectations all interacted to shape the emergent learning ecology. Faculty reflections similarly revealed the need for stronger pedagogical integration and team teaching across course components, as disciplinary separation sometimes reproduced epistemic divisions rather than dissolving them.

CoP - Transformative Encounters and Mutual Learning

A central finding of this iteration was the strong value students placed on learning from one another's disciplinary perspectives. Engineering and visual arts students reported increased openness, empathy, and appreciation for multidisciplinary collaboration. In well-integrated teams, members began adopting aspects of each other's thinking: artists increasingly considered technical constraints in aesthetic decisions, while engineers incorporated artistic criteria into design reasoning.

Students reflected on how collaboration expanded their ability to function across disciplinary boundaries: *"I learnt to communicate with individuals of different mindset than me and different capabilities as well. It was refreshing, I would say. I'm already a very open and patient person, but it really made me develop those skills of being a team player and understanding that others are either limited to certain things or others are not limited to certain things." (I4 T12 Eng Male)*

Similarly, exposure to artistic thinking altered engineering perspectives: *"Our ways to approach projects typically would be more in technical terms — like, it has to meet these physical aspects, it has to weigh at most this much, and it has to be this size. In general, the three artists in our group will look at it more as being like it has to look more this way, not so much it has to be this size. I know that's changed this perspective a lot, because now in the back of my head, I'm always thinking 'Does it look the way we want?'" (I4 T14 Eng Male)*

Students also emphasised how diversity of strengths enhanced collaboration: "*There's lots of value in having different strengths in this team. Having a diverse team can help a lot. Yes, because we're two painters, and she's a photographer, and they are civil and electrical, so it's a little bit of everything I guess." (I4 T14 Art Female)*

Initial stereotypes, however, revealed apprehensions: *"We were worried about them not wanting to work with us because we're art students." (I4 T14 Art Female)* , *"Well, yeah, I heard things about engineers being difficult to work with… But that ended up not being the problem after all… it wasn't about the stereotype, just the whole language barrier." (I4 T12 Art Female)*

Over time, teams realised differences were smaller than expected: *"I still feel, like, for me, I can see the differences. But it's not like you guys are totally different… Coming in, you think there's going to be a huge difference… but it's subtle." (I4 T14 Eng Male)*

Student reflections revealed that stereotypes between artists and engineers gradually dissolved when collaboration occurred within safe, shared learning environments. Students increasingly self-organised around interests and skills rather than disciplinary labels, suggesting that flexible role assignment better supports integration than rigid discipline-based task divisions.

Epistemic Reflexivity - Communication Challenges

Despite overall success, communication difficulties marked early collaboration stages. Disciplinary lexicons initially created confusion and hindered mutual understanding. Both engineers and artists reported needing to translate terminology and conceptual frameworks for teammates. One engineering student humorously described the challenge: *"At the beginning, there were words that the artists were using that I just didn't understand — I had never heard before. Like, "motif" was one of them [laughs] — I don't even know how to spell it [laughs], forget about it. [laughs]." (I3-T2 Eng Male)* An art student similarly explained reciprocal misunderstandings: *"Some of their terminology … would mean something totally different, … So, then I'm like, 'wait, you need to explain that.' And then, sometimes the same with us too …" (I4 T14 Art Female)*

Another student summarised the contrast in disciplinary approaches: *"This clash of functionality and structure against artistic creativity and freedom… highlights the differences in how engineers and artists design things. Engineers plan everything out… while artists… adapt as they move forward." (I4 T6 Art Female)* Yet overcoming these differences often became a powerful learning experience. Contrary to initial assumptions, many engineering students welcomed arts-based challenges: *"At first, I didn't really know what to make of it… But… I'm glad I stuck with it. In the end it turned out to be pretty fun, and we still learnt a lot." (I4 T14 Art Female)*

When project briefs successfully bridged technical and artistic concerns, students engaged deeply regardless of disciplinary identity. Structured onboarding tools—shared glossaries, concept-mapping sessions, and early co-reflection exercises—could further ease epistemic bridging in future iterations.

Epistemic Empathy and Control

Perhaps the most profound transformations reported by students reflected the emergence of epistemic empathy—the ability to appreciate others' cognitive and methodological orientations—and epistemic control—the capacity to adjust one's own contributions considering this understanding.

Students increasingly approached projects with awareness of collective goals rather than individual disciplinary priorities. One engineering student described a lasting shift in career orientation: *"I want [this work] to be influenced by art and design… I'm not looking to do regimented, strictly engineering work anymore." (I4 T2 Eng Male)* Such reflections demonstrate that collaboration reshaped not only projects but also students' professional aspirations and identities.

Overall Insight

Iteration 4 confirmed that transdisciplinary collaboration requires intentionally designed learning ecologies supporting emotional safety, epistemic negotiation, and shared purpose. As students navigated differences in language, methods, and values, they developed new ways of seeing, making, and relating. Art students gained confidence in technical contexts, while engineering students engaged more deeply with ambiguity, aesthetics, and meaning-making.

TD-SDT components proved critical in enabling this transformation. Knowledge was not transmitted but co-constructed, enabling communities of practice in which students learned with and from one another. Challenges encountered—including faculty coordination and communication mismatches—were not failures but indicators of areas requiring stronger pedagogical integration and scaffolding.

Iteration 4 therefore both validated TD-SDT principles and highlighted the work required to institutionalise such collaboration. It demonstrated that friction, when constructively engaged, can become a driver of innovation rather than an obstacle. Students' experiences suggest that TD-SDT operates not only as a conceptual framework but as a practical methodology capable of shaping cognitive, affective, and collaborative dimensions of learning.

These findings set the stage for the next section, which examines the concrete concepts and tools constituting the evolving TD-SDT across the first four research iterations.

4.5.4.2 TD-SDT Evolution

Iteration 4 confirmed that the TD-SDT can effectively support transdisciplinary knowledge creation within the temporal and institutional constraints of a standard 12-week course, demonstrating that extended internship formats are not the only viable conditions for TD emergence. The iteration validated previously identified components—equal footing, community of practice, productive friction, epistemic reflexivity, and authentic public engagement—while revealing the need for stronger scaffolding around communication, disciplinary language bridging, and integrated teaching practices. Findings showed that co-location alone does not generate integration; rather, carefully designed learning ecologies must actively support epistemic negotiation, emotional safety, and collaborative risk-taking. This iteration therefore refined the TD-SDT by emphasising onboarding processes, shared facilitation strategies, and flexible role structures as critical mechanisms for enabling integration under tighter academic constraints.

These findings further refined the TD-SDT (Table 21) by demonstrating that successful integration depends not only on collaborative tools but also on relational infrastructures that support epistemic negotiation and shared authorship.

Table 21 Evolution of the TD-SDT - After Iteration 4

TD-SDT Dimensions	Concept	Representative Tools / Practice	Iteration Introduced
Ambiguity	Tolerance for uncertainty	Open challenge: with few constraints (helps creativity)	3-4
Trust	Psychological safety for collaboration	Safe-space creation - create & protect safe-space for vulnerability	3-4
		Informal team building (shared meals, games)	3-4
		Team-level decision making	3-4
Epistemic Reflexivity	Awareness of disciplinary assumptions	Discipline appropriate recruiting / scaffolding	1
		ITP Metrics – Personality Types	2
		Recognition of epistemic differences (artists focus on *Why*, engineers focus on *How*)	3
Epistemic Humility	Equal participation across disciplines	Equal Footing in collaboration	3-4
		Stereotype deconstruction	3-4

Epistemic Friction	Productive negotiation of difference	Productive friction, and slowing decision process	3-4
Mutual Learning	Community-based knowledge exchange	Community of Practice	3-4
		Process-driven approach	3-4
		Student-centred approach	3-4
		Team Contract	2-4
Epistemic Boundary Mediation	Boundary Object	Prototypes, shared lexicon, collaborative artifact	3-4
Enabling Infrastructu re	Project organisation	Design Thinking / Double-Diamond	2-4
		Client / art-client-model	2-4
		Iterative Prototyping	2-4
Art-Studio Pedagogies	Artistic inquiry methods	Object-Based Enquiry	2-4
		Critique (feedback)	2-4
		Exhibit of Artifacts.	2-4
Artistic Exposure	Artistic reference and inspiration	Curated art presentation	2-4
		Artist Talk	3-4

4.5.4.3 Contribution of Iteration 4 — *Structured Multidisciplinary Learning Environment*

Iteration 4 examined whether the relational and epistemic conditions identified during the internship could be reproduced within a structured course environment. The findings showed that carefully scaffolded collaboration supported multidisciplinary teamwork within academic constraints, confirming the importance of deliberate TD-SDT scaffolding. This iteration therefore shifted the research focus toward refining how TD-SDT components can be systematically designed and reproduced across diverse educational contexts.

4.6 Conclusion Chapter 4 – TD-SDT Foundation

This chapter presented the first four action-research iterations through which the Transdisciplinary STEAM Design Toolkit (TD-SDT) was progressively developed and refined. The findings demonstrate how transdisciplinary collaboration evolved from initial multidisciplinary juxtaposition toward deeper forms of knowledge integration as recruitment strategies, process scaffolding, and relational conditions were progressively introduced. Together, these iterations established the empirical foundations of the TD-SDT by identifying the epistemic, relational, and pedagogical conditions required to support transdisciplinary STEAM collaboration in educational contexts.

The first four iterations of this study established the foundational development of the *Transdisciplinary STEAM Design Toolkit (TD-SDT)*. Across these early cycles, the research documented a progression from multidisciplinary juxtaposition toward more integrated forms of transdisciplinary knowledge creation. Interpreted through the *Constructivism–Systems Thinking–Complexity (CSC) framework*, these iterations revealed the conditions required for teams to move beyond disciplinary silos and engage in collaborative meaning-making.

Constructivist Implications – Disrupting Epistemic Silos

From a constructivist perspective, knowledge is situated and co-constructed rather than a neutral reflection of reality. Iteration 1 revealed a pronounced divide between arts and engineering students, demonstrating that without intentional recruitment and scaffolding, participants remained embedded within their disciplinary cultures. Iteration 2 introduced design thinking as a shared process language; however, positioning art primarily as a client requirement often resulted in technical augmentation rather than deeper epistemic integration.

More substantial constructivist shifts emerged in Iterations 3 and 4. Practices such as equal footing and structured reflexive dialogue enabled students to move beyond disciplinary representation toward co-authorship of shared meaning. Boundary objects—particularly prototypes and shared conceptual artifacts—served as mediating structures through which divergent interpretations could be negotiated and integrated.

Systems Implications – Building Relational Infrastructure

From a systems perspective, STEAM collaboration functioned as a relational ecology rather than a set of independent disciplinary contributions. Across iterations, trust and communication operated as stabilising feedback loops: when these relational mechanisms weakened, collaborative progress stalled. Conversely, when epistemic tensions were constructively engaged, they became leverage points enabling deeper integration.

For example, in Iteration 3, one team's decision to confront rather than avoid epistemic friction catalysed a systemic shift in collaboration dynamics, enabling movement from interdisciplinary coordination toward transdisciplinary innovation. These observations highlight the importance of relational infrastructures—such as trust-building practices, shared decision-making, and communicative mediation—as essential scaffolding within the TD-SDT.

Complexity Implications: Designing for Emergence

Complexity theory frames collaboration as nonlinear and emergent. The findings across Iterations 1–4 indicate that transdisciplinary outcomes cannot be prescribed in advance; rather, they emerge through sustained interaction, ambiguity tolerance, and iterative experimentation. Highly original artifacts were associated with teams that remained in productive uncertainty and engaged moments of hesitation as opportunities for inquiry rather than failure.

Iteration 3 provided the clearest illustration of this dynamic, where the most original artifacts emerged from teams that remained within conditions of ambiguity and negotiation. By Iteration 4, it became evident that such emergent dynamics were not accidental. Within a structured twelve-week course environment, transdisciplinary integration could still be fostered when teaching teams intentionally calibrated ambiguity and actively facilitated productive friction between disciplinary approaches.

Synthesis – Establishing the TD-SDT Foundation

Taken together, Iterations 1–4 demonstrate that transdisciplinary collaboration does not arise spontaneously from disciplinary proximity. Instead, it requires intentional scaffolding, structured reflexivity, and the careful design of relational conditions that support epistemic negotiation.

Across these early cycles, several foundational principles emerged:

Trust functioned as a stabilising condition enabling vulnerability and epistemic risk-taking.

Friction, when constructively engaged, operated as a generative driver of integration rather than a barrier.

Equal Footing shifted teams from disciplinary service roles toward co-creative authorship.

Community of Practice (mutual learning) structures provided relational continuity through which participants moved from disciplinary newcomers to integrated collaborators in a shared transdisciplinary space.

These findings position the TD-SDT not simply as a collection of pedagogical tools but as an emerging design infrastructure for navigating epistemic difference within complex collaborative environments. While achieving transdisciplinary integration remains challenging, the research demonstrates that it is a scaffolded and learnable process capable of reshaping both participants and the knowledge they co-create.

This foundation sets the stage for the next phase of the research. Chapter 5 builds on these insights by operationalising the TD Process Assessment Framework and examining later iterations (5–7), where the TD-SDT was implemented more systematically and evaluated across teams and contexts.

TD-SDT Evolution

Table 22 summarises the progressive evolution of the Transdisciplinary STEAM Design Toolkit (TD-SDT) across Iterations 1–4. The table highlights the epistemic, relational, and pedagogical components that emerged through the action-research cycles and that together form the foundational architecture of the framework.

Table 22 Evolution of the TD-SDT Across Iterations 1–4

TD-SDT Dimensions	Concept	Representative Tools / Practice	Iteration Introduced
Ambiguity	Tolerance for uncertainty	Open challenge: with few constraints (helps creativity)	3-4
Trust	Psychological safety for collaboration	Safe-space creation - create & protect safe-space for vulnerability	3-4
		Informal team building (shared meals, games)	3-4
		Team-level decision making	3-4
Epistemic Reflexivity	Awareness of disciplinary assumptions	Discipline appropriate recruiting / scaffolding	1
		ITP Metrics – Personality Types	2
		Recognition of epistemic differences (artists focus on *Why*, engineers focus on *How*)	3
Epistemic Humility	Equal participation across disciplines	Equal Footing in collaboration	3-4
		Stereotype deconstruction	3-4
Epistemic Friction	Productive negotiation of difference	Constructive friction (Productive Friction Point) and slowing of the decision process	3-4

Mutual Learning	Community-based knowledge exchange	Community of Practice	3-4
		Process-driven approach	3-4
		Student-centred approach	3-4
		Team Contract	2-4
Boundary Objects	Shared artifacts mediating collaboration	Prototypes, shared lexicon, collaborative artifact	3-4
Enabling Infrastructu re	Project organisation	Design Thinking / Double-Diamond	2-4
		Client / art-client-model	2-4
		Iterative Prototyping	2-4
Art-Studio Pedagogies	Artistic inquiry methods	Object-Based Enquiry	2-4
		Critique (feedback)	2-4
		Exhibit of Artifacts.	2-4
Artistic Exposure	Artistic reference and inspiration	Curated art presentation	2-4
		Artist Talk	3-4

The table illustrates how the TD-SDT progressively expanded from initial recruitment and epistemic awareness mechanisms (Iteration 1) to process scaffolding tools (Iteration 2) and ultimately to relational and epistemic conditions enabling deeper integration (Iterations 3–4). Together, these components constitute the foundational configuration of the TD-SDT framework.

Contribution of iterations 1-4 -- Foundational architecture of the TD-SDT

Across Iterations 1–4, analysis of the action research cycles revealed three categories of enabling conditions for transdisciplinary STEAM collaboration: epistemic conditions related to recognising and negotiating disciplinary knowledge differences; relational conditions supporting trust, equal footing, and productive friction; and pedagogical conditions structuring collaborative learning environments. These conditions emerged progressively from the empirical findings and informed the development of the Transdisciplinary STEAM Design Toolkit (TD-SDT).

Together, these findings establish the foundational architecture of the TD-SDT, identifying the epistemic, relational, and pedagogical conditions that enable transdisciplinary knowledge creation and preparing the ground for the systematic evaluation presented in the following chapters.

Chapter 5 Operationalising TD Process Assessment & Refining TD-SDT - Iterations 5 - 7

5.1 Introduction

Chapter 4 documented the progressive emergence of the Transdisciplinary STEAM Design Toolkit (TD-SDT) through the first four action research iterations. These cycles clarified the epistemic, relational, and pedagogical conditions required to support transdisciplinary collaboration in STEAM education. Having established this foundational framework, the next phase of the research focuses on its systematic implementation and evaluation. Chapter 5 therefore operationalises the TD Process Assessment Framework and examines later iterations (5–7), analysing how TD-SDT components influence collaboration dynamics, disciplinary integration, and transdisciplinary knowledge creation across teams and contexts.

Whereas Chapter 4 focused on identifying the enabling conditions for transdisciplinary collaboration, Chapter 5 evaluates how these conditions influence the quality of collaboration and integration across student teams.

This chapter marks a methodological shift from developmental narrative to systematic assessment. It operationalises and empirically applies the TD Process Assessment Framework (Table 23; APPENDIX F), introduced conceptually in Section 3.7 and grounded theoretically in Section 2.6.

Table 23 TD Process Assessment Framework

TD Process Assessment Framework			
TD Process Quality – TD Collaboration			**TPQ Score**
	Collaborative Process	C1- Trust	L/M/H [0,3]
		C2- Communication	
		C3- Mutual Learning	
		C4- Conflict Handling (Friction)	
		C5- Shared Problem Framing	
	Reflexivity	C6- Equal footing, Power relationships & fairness	
		C7- Team Critical Self-Awareness	
TD Integration Quality – TD Knowledge Creation (Tangible)			**TIQ Score**
	Artifacts Created	K1- Epistemic (Disciplinary) Grounding	L/M/H [0,3]
		K2- Integration Depth & Coherence	
		K3- Advancement of Understanding (novelty)	
TD Societal Effects – TD Knowledge Creation (Intangible)			**TSE Score**
	Learning & Capacity Building of Participants	K4- Cognitive, social & practical competencies	L/M/H [0,3]
	Societal Usefulness	K5- Salient, credible, legitimate, actionable	
	Societal Impacts	K6- Policy & Practices Change	
TD Process Score [0,9] where: Low =[0,2]; Medium=[3,5]; High=[6,9]			**TD Process Score**

The chapter serves two interrelated purposes.

First, it advances a methodological contribution by translating the TD Process Assessment Framework into a structured analytic instrument. This includes specifying the assessment architecture, coding procedures, rubric design, scoring logic, and workflow used to evaluate transdisciplinary collaboration and knowledge creation. In doing so, the chapter formalises the link between TD-SDT components and measurable collaborative and epistemic outcomes.

Second, it applies this instrument to Iterations 5, 6, and 7. While earlier cycles focused on toolkit emergence and refinement, these later iterations implemented TD-SDT components more systematically within structured pedagogical designs. Each iteration is examined as a distinct action research cycle using the Plan–Act–Observe–Reflect structure, enabling comparative analysis of collaborative dynamics (C-dimensions), knowledge integration and novelty (K-dimensions), and societal orientation across teams and contexts.

Because the TD Process Assessment Framework was consolidated following the completion of data collection, its operationalisation reflects a retrospective and reflexive logic consistent with action research and design-based inquiry. Rather than imposing predetermined evaluative criteria, the framework was inductively derived through iterative engagement with the longitudinal dataset and relevant assessment scholarship. It was then applied systematically to enable structured cross-team and cross-iteration comparison.

Operationalisation integrates hybrid deductive–inductive thematic coding, rubric-based scoring, artifact analysis, and triangulation across interviews, reflective journals, prototypes, and researcher documentation. Through this structured analytic approach, the chapter moves from conceptual architecture to empirical instrumentation.

Chapter 5 constitutes the analytic core of the dissertation. It demonstrates how transdisciplinary collaboration and knowledge creation can be rendered visible, comparable, and assessable—thereby advancing the thesis's broader aim of making Transdisciplinary STEAM intentional, scaffolded, and rigorously examined within complex educational systems.

5.2 From Conceptual Framework to Operational Instrument

Chapter 3 introduced the TD Process Assessment Framework as the conceptual lens used to examine how transdisciplinary knowledge creation emerged through collaborative processes. The present section describes how this framework was operationalised in the analysis of the empirical data.

The analytical procedure began with the systematic extraction of evidence from multiple data sources, including student interviews, reflective journals, final project reports, project artifacts, and researcher observations. Drawing on these diverse sources allowed the analysis to capture both the observable outcomes of the design process and the reflective insights of participants regarding their collaborative experiences. This multi-source approach aligns with the Constructivism–Systems Thinking–Complexity (CSC) framework underpinning this research, which views knowledge creation as emerging through interactions among actors, artifacts, and contexts rather than through isolated individual contributions.

The extracted evidence was then interpreted using the structured rubrics defined within the TD Process Assessment Framework. These rubrics enabled consistent evaluation of transdisciplinary process dimensions and associated outcomes. Through this interpretive step, qualitative observations were translated into structured assessments while preserving contextual evidence from the data.

Following this interpretation stage, findings were synthesised at the team level to capture the collaborative dynamics through which knowledge creation unfolded within each project team. These team-level assessments were subsequently aggregated at the iteration level to identify broader patterns across teams working within the same pedagogical context. This multi-level analysis reflects a systems-oriented perspective, allowing patterns of interaction, learning, and integration to be examined across individuals, teams, and iterations.

In parallel, a structured attribution process was conducted to examine how specific TD-SDT concepts and tools contributed to the observed collaboration dynamics and knowledge creation processes. This step allowed the analysis to connect observed team behaviours and outcomes to the pedagogical conditions introduced through the toolkit.

As illustrated in Figure 8, the overall analytical workflow was organised into four stages: initial data preparation, team-level assessment repeated for each team, iteration-level aggregation, and cross-source triangulation. Throughout the analysis, the team was treated as the primary unit of analysis, reflecting the collaborative locus through which transdisciplinary knowledge creation emerged within the learning environment.

5.2.1 Data Preparation and Unit Structure

Data were organised hierarchically by iteration, team, and individual contributor to support both within-team analysis and cross-iteration comparison. This hierarchical structure enabled the analysis to examine how collaborative processes and design outcomes evolved across multiple

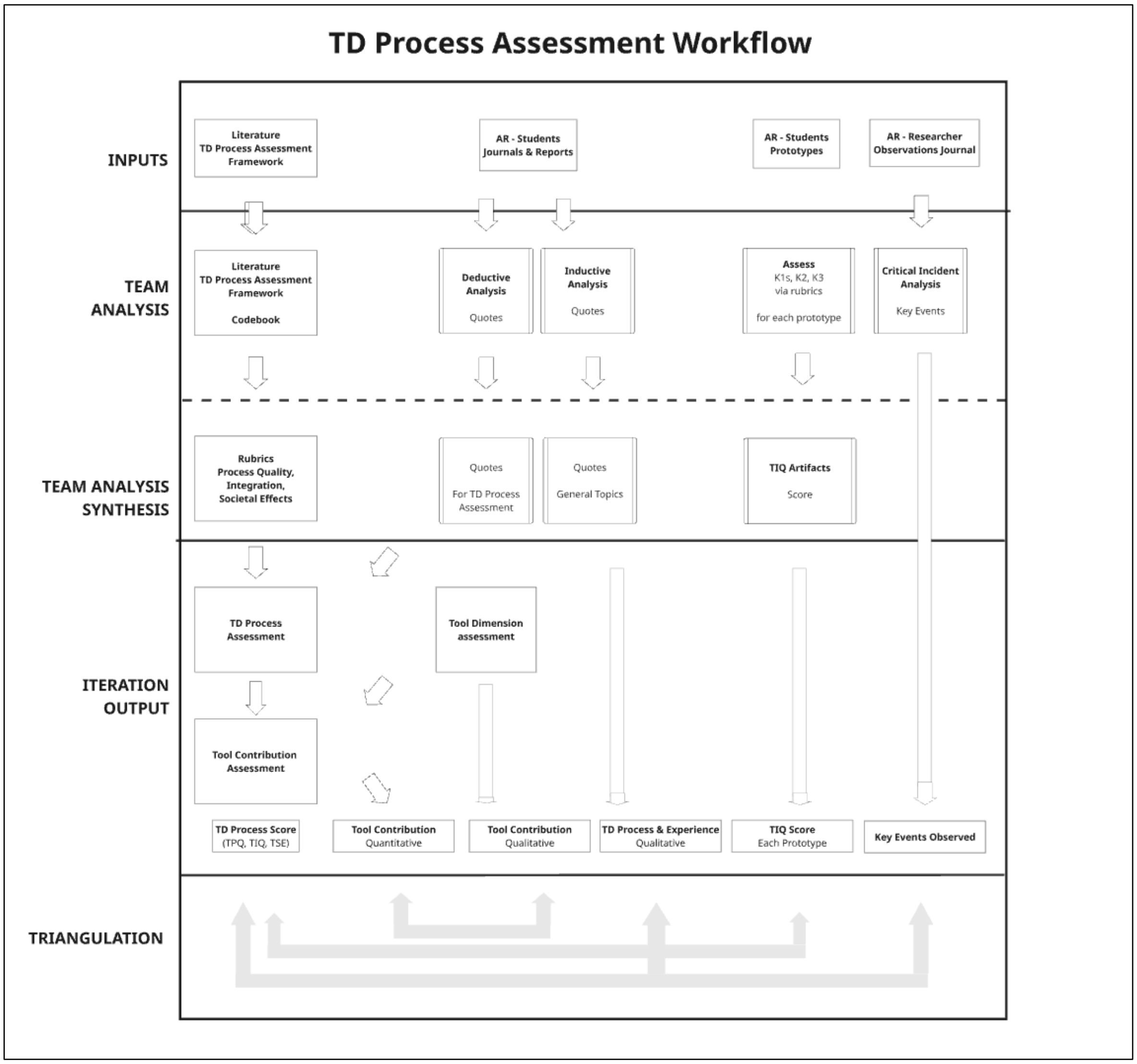


Figure 8 TD Process Assessment Workflow (replicated from chapter 3)

pedagogical contexts while maintaining visibility into individual contributions within each team.

For each team, an assessment case file was compiled that consolidated the various sources of evidence generated throughout the design process. These case files included collated reflective journals, interview transcripts from earlier iterations, final project reports, prototype documentation and final artifacts, as well as researcher reflective notes. Bringing these materials together within a single case file allowed multiple perspectives on the design process to be examined in relation to one another.

To preserve longitudinal traceability while enabling triangulation across data sources, individual reflective journals were consolidated by contributor. This organisation made it possible to follow the evolution of each participant's reflections over time while situating those reflections within the broader collaborative dynamics of the team.

By structuring the data in this way the analysis-maintained coherence across multiple levels of observation linking individual experiences, team-level interactions, and iteration-level outcomes. This case-based organisation also provided a transparent audit trail for the interpretation and scoring procedures applied in the subsequent stages of the TD Process Assessment Framework.

This structured organisation of the data provided the evidentiary foundation for the subsequent interpretation and rubric-based scoring procedures of the TD Process Assessment Framework, ensuring that all assessments remained traceable to the underlying qualitative evidence.

5.2.2 Coding and Rubric-Based Assessment

Text-based sources, including reflective journals, interview transcripts, and final reports, were analysed using a hybrid deductive–inductive thematic approach following the procedures outlined by Braun & Clarke (2006). This approach enabled the analysis to both apply predefined analytical categories and remain open to patterns emerging from the data.

During the deductive coding phase, the TD Process Codebook was applied to identify evidence corresponding to the dimensions of the TD Process Assessment Framework (C1–C7; K1–K6). In parallel, instances of TD-SDT tool usage were extracted to examine how specific pedagogical conditions contributed to the observed collaboration processes and knowledge creation outcomes.

The inductive phase of the analysis focused on identifying emergent themes and capturing unexpected patterns that were not fully anticipated by the predefined framework. This combination of deductive and inductive analysis allowed the coding process to remain both theoretically grounded and empirically responsive to the data.

The resulting coding generated dimension-specific evidence sets, which were subsequently used to support rubric-based scoring of the three core outcome categories: TD Process Quality (TPQ), TD Integration Quality (TIQ), and TD Societal Effects (TSE). Scores ranging from 0 to 3 were assigned using structured descriptors and supported by traceable qualitative justification drawn from the coded evidence.

Throughout the analysis, the TD Process Codebook was iteratively refined to improve analytic clarity and coding consistency as patterns in the data became more apparent.

These rubric-based assessments formed the basis for the subsequent team-level synthesis and iteration-level aggregation described in the following section.

5.2.3 TD Process Assessment Structure

The TD Process Assessment is composed of three interrelated components that together capture the key dimensions of transdisciplinary knowledge creation. The first component, TD Process Quality (TPQ), examines the quality of collaboration within teams and is assessed through the dimensions C1–C7. The second component, TD Integration Quality (TIQ), evaluates the degree of tangible knowledge creation achieved through the integration of disciplinary perspectives, and is assessed through the dimensions K1–K3. The third component, TD Societal Effects (TSE), addresses intangible learning outcomes associated with transdisciplinary engagement, represented by the dimensions K4–K6.

Each component was evaluated using a structured rubric with scores ranging from 0 to 3. These scores were subsequently aggregated to produce both team-level and iteration-level TD Process Scores, allowing patterns of collaboration and knowledge creation to be examined across teams and pedagogical contexts.

Assessment of TD Integration Quality (TIQ) was supported through triangulation across multiple forms of evidence. The primary evaluation was conducted through artifact-based scoring ($TIQ_{artifact}$), which assessed the degree of disciplinary integration reflected in the final prototype and design documentation. This assessment was complemented by quote-based scoring (TIQ_{quote}), which examined reflective statements from students to validate the presence of integrative thinking and collaborative learning processes.

Within the TD Societal Effects (TSE) dimension, only K4 (Learning and Capacity Building) was empirically assessed in this study. This limitation reflects the academic context of the project, in which broader societal outcomes such as policy influence or long-term behavioural change could not be directly measured within the timeframe of the educational intervention.

Through this structured scoring system, the TD Process Assessment Framework functions as a transparent empirical instrument, enabling systematic evaluation of transdisciplinary collaboration and knowledge creation rather than remaining a purely descriptive conceptual model.

The resulting TD Process Scores provide the basis for the team-level assessments and iteration-level comparisons presented in the following sections.

5.2.3.1 TD Process Quality (TPQ)

TD Process Quality—operationalised with two process categories: collaboration and reflexivity—was assessed using seven process dimensions (C1–C7): trust (C1), communication (C2), mutual learning (C3), conflict handling/friction (C4), shared problem framing (C5), equal footing/power relations and fairness (C6), and team critical self-awareness (C7).

Assessment was conducted at the team level using structured rubrics (APPENDIX H) anchored in extracted qualitative evidence. Evidence was drawn from reflective journals, interviews, team reports, and researcher notes. For each team, quotations were coded deductively using the TD Process Codebook (APPENDIX F), grouped by dimension, and compiled into team-specific evidence sets. Scores were then assigned using a 0–3 ordinal scale (0 = not observable/not applicable; 1 = low; 2 = moderate; 3 = strong), guided by the rubric descriptors and indicators provided in APPENDIX H.

5.2.3.2 TD Integration Quality (TIQ)

TD Integration Quality (TIQ) was assessed through K1–K3 dimensions, which were operationalised using rubric-based assessment:

- **K1 – Disciplinary Grounding (Epistemic Grounding)** (APPENDIX I),
- **K2 – Integration Depth and Coherence** (APPENDIX J), and
- **K3 – Advancement of Understanding (Novelty)** (APPENDIX K).

The *TIQ Score* reflects the integration quality of each team's final artifact which is assessed in two separate ways allowing triangulation. First, it is assessed using the artifacts, a process referred to as $TIQ_{artifact}$ *Scoring* and second it is assessed using the extracted student quotes obtained from deductive analysis, a process referred to as *TIQ_{quote} Scoring*. *$TIQ_{artifact}$ Scoring* carries more information since it is assessed directly from the artifacts, therefore carries more weight in the TIQ analysis. Both methods are reviewed here and applied in Iteration 5.

TIQ_{quote} Scoring Method

This assessment method follows the *TD Process Quality (TPQ)* assessment method described above (Section 5.2.3.1) using rubrics for K1, K2, K3 found in APPENDIX I, J and K.

$TIQ_{artifact}$ Scoring Method

$TIQ_{artifact}$ Scoring (or $TIQS_{artifact}$) is an analytical instrument applied to tangible outputs (artifacts, and prototypes) to evaluate the extent to which STEAM design outcomes demonstrate disciplinary synthesis and epistemic advancement beyond juxtaposition. This method assesses the integration quality of tangible outputs (K1–K3) through systematic analysis of each team-produced artifact.

Each prototype's TD Integration Quality (TIQ) was assessed using these three dimensions. Disciplinary Grounding (K1) was assessed based on the artifact for each participating discipline and the results were averaged to obtain the final K1 value; K2 and K3 were assessed based on evidence from artifacts, and process documentation. Scores were assigned on a 0–3 scale and documented with artifact-specific justifications to ensure transparency and traceability.

$TIQ_{artifact}$ Scoring Calculations

$TIQS_{artifact}$ was calculated using the following formula:

$$\mathbf{TIQS}_{artifact} = \mathbf{Avg\ (\ Avg\ (K1s),\ K2,\ K3)}$$

where :

K1s denotes disciplinary grounding scores [0-3] assessed per discipline and averaged.
K2 and K3 are each assessed on [0-3] scale.

Scores range from 0 (no meaningful integration) to 3 (transformative integration), with higher scores indicating coherent synthesis and novelty that transcend disciplinary boundaries.

The **$TIQS_{artifact}$** method was piloted on artifacts from Iterations 3 and 4 with two disciplinary assessors (from arts and engineering) to calibrate rubrics and scoring criteria. Pilot testing revealed limitations of a posteriori assessment based solely on photographs and brief descriptions—

particularly for experiential and interactive works. Final scoring was therefore conducted by the primary researcher with access to richer contextual and process information, while maintaining artifact-specific evidence logs to support analytical rigor.

Prototype-level K1–K3 scores were combined to produce final $TIQ_{artifact}$ values, which were aggregated for each team at the iteration level.

TIQ_{quote} Scoring and $TIQ_{artifact}$ Triangulation

Once the K1, K2, K3 values were obtained through both methods, they were compared to valid when values were similar and investigated when values were largely divergent and final TIQS values were obtained and appear in the final TD Process Assessment Framework.

5.2.3.3 TD Societal Effects (TSE)

TD Societal effects (TSE) of TD knowledge creation were conceptualised using dimensions K4–K6: learning and capacity building (K4), societal usefulness (K5), and societal impact (K6).

In this study, empirical assessment was constrained by the academic context. Although projects addressed socially and environmentally relevant challenges, artifacts were not deployed in real-world policy or community settings. Accordingly, only K4 was assessed empirically, capturing cognitive, social, and practical competencies developed through TD collaboration. K5 and K6 are retained conceptually to preserve the framework's completeness and future applicability but are explicitly marked as not assessed in this study.

K4 was assessed using a structured rubric aligned with the framework (APPENDIX K) and the same 0–3 ordinal scale. Scoring was grounded in qualitative indicators drawn primarily from journals, interviews, and researcher observations, supported by representative excerpts for traceability and triangulation.

In sum, the TD Process Assessment was operationalised as a structured, multi-layered analytical system integrating qualitative coding, rubric-based scoring, artifact evaluation, and triangulation across data sources. By systematically assessing TD Process Quality, TD Integration Quality, and TD Societal Effects at both team and iteration levels, the framework functioned not merely as a conceptual model but as an empirical instrument. This operationalisation enabled theoretically grounded yet context-sensitive evaluation of transdisciplinary collaboration and knowledge creation, while ensuring transparency, traceability, and methodological rigor across iterations.

5.2.4 TD-SDT Concept/Tool Contribution Assessment

The analysis of TD-SDT concept–tool contributions to TD collaboration and TD knowledge creation draws on the TD Process Assessment dimensions theoretically expected to be activated (Section 2.6). The mapping between concept–tool pairs and TD Process dimensions is provided in APPENDIX L. For each concept–tool pair, the mapping identifies: (a) the primary TD collaboration dimensions (C1–C7) and (b) the TD knowledge creation dimensions (K1–K4) it is theoretically expected to support, along with key supporting sources. This mapping establishes the theoretical foundation for contribution analysis in Chapter 5.

Tool effectiveness is not treated as causal. Instead, tools are conceptualised as operational infrastructure whose contribution is inferred through their patterned relationship to observed TD collaboration and knowledge creation outcomes, supported by convergent qualitative evidence.

5.2.4.1 Operational Tool-Dimension Mapping

The concept–tool to dimension mapping, derived from seminal literature introduced in Chapter 2, is used instrumentally in this chapter to determine which TD Process dimensions are relevant when assessing a given tool. For example, the concept/tool pair *Building Trust–Vulnerability* is mapped to trust (C1) and equal footing (C6) and is theorised to support learning and capacity building (K4) (Edmondson, 2012; Levin & Cross, 2004).

This mapping does not predetermine outcomes; rather, it defines the analytical scope within which tool contributions are examined.

5.2.4.2 Team-Level Concept/Tool Contribution Calculation

At the team level, tool contribution was estimated by aggregating the TD Process Assessment scores associated with the dimensions activated by a given concept–tool pair. This structured attribution approach enables systematic comparison of relative contributions while avoiding deterministic or causal claims.

Specifically, the contribution value of a TD-SDT concept/tool pair for a given team was calculated by summing the scores obtained on its mapped dimensions within the TD Process Assessment Framework. For example, if a concept/tool pair activates dimensions C1, C6, and K4, and the team's scores for these dimensions are 3, 0, and 2 respectively, the tool contribution value for that team equals 5.

This quantitative attribution was interpreted alongside qualitative evidence to preserve contextual nuance.

Triangulation was applied where possible to strengthen credibility and reduce reliance on single-perspective accounts (Lincoln, 1985). In addition to student-generated data, the researcher's reflective journal was analysed to identify key events, contextual conditions, and critical incidents that informed interpretation of collaborative dynamics.

5.2.5 TD Process Assessment Summary

Following team-level assessments of TD Process Quality (TPQ), TD Integration Quality (TIQ), and TD Societal Effects (TSE), results were aggregated at the iteration level, treating the iteration as the unit of synthesis. Tool contribution profiles—calculated through predefined dimension mappings—were interpreted using a dual assessment strategy combining quantitative aggregation and qualitative validation through coded student quotations and thematic evidence. Computed contribution patterns were triangulated across journals, reports, artifacts, and researcher observations to confirm or problematise inferred relationships. Critical incident analysis further contextualised breakdowns, tensions, and unexpected successes, identifying boundary conditions shaping TD collaboration and knowledge creation. Change was tracked both within teams and across iterations, enabling cross-iteration comparison interpreted through the CSC lens and STEAM guiding principles to support progressive refinement of the TD-SDT.

Having established the operationalisation of the TD Process Assessment Framework as a structured assessment instrument, the following sections apply this framework to the empirical analysis of Iterations 5, 6, and 7. Each iteration is examined as a distinct action-research cycle using a Plan–Act–Observe–Reflect structure, enabling systematic evaluation of TD collaboration processes, knowledge integration, learning outcomes, and the contribution of TD-SDT concept/tool pairs at the team and iteration levels.

5.3 Iteration 5 - A Model for STEAM Design Course (2020)

Iteration 5 built on insights from Iteration 4, which demonstrated the value of embedding TD-SDT components directly within a unified class environment. A key refinement involved ensuring that all students worked together during shared instructional time to maximise opportunities for transdisciplinary engagement.

5.3.1 Plan - Iteration 5

5.3.1.1 STEAM Design Challenge and Research Focus

STEAM Design Challenge: In iteration 5, students were asked to conceive and design small-scale functional prototypes of interactive art installations to answer the question: "What is the most urgent environmental problem for you?" The final artifact had to deal with a key environmental issue of their choice, using any technique and any art form.

TD-SDT Research Focus: In this iteration, several concept–tool pairs were introduced or revisited to examine their potential contribution to the evolving components of the Transdisciplinary STEAM Design Toolkit (TD-SDT). The iteration revisited *Community of Practice (CoP)* and *Reflexivity* through the tools *Teach-a-Skill* and *ITP Metrics*, both of which had demonstrated promising effects in earlier iterations. In addition, new pedagogical conditions were introduced to support *ambiguity tolerance* and *transdisciplinary cognitive skills*. These included the use of an *open challenge* to increase project ambiguity, as well as activities activating three of *Henriksen's seven Transdisciplinary Cognitive Skills (TCS)—perceiving, abstracting, and playing*. To support these skills, *formal analysis* was introduced as a tool for developing perceptual awareness, while *LEGO® Serious Play®* (Lego, 2019) was used to encourage metaphorical thinking and playful abstraction. The following sections describe how these tools were implemented in the course.

5.3.1.2 Data Collection & Analysis Plan

At this point in the development of our STEAM initiatives, semi-structured interviews were replaced with student reflective journals to get students' reflections as the experience unfolded. According to (J. S. Brown et al., (1989), over time the journal entries trace a growing depth of insight, the active negotiation of disciplinary differences, and the gradual emergence of integrative thinking. So, four student reflective journals were submitted as blog assignments 1, 3, 4 & 5 during the course at weeks 2, 6, 8 & 12. Reflective journal questions can be found in APPENDIX O.

Other data collected included team final reports, final artifacts, prototypes and researcher's journal for observation notes.

The text-based data sources (student reflective journals and final reports) provided evidence to support the impact of TD-SDT components on TD Collaboration and TD knowledge Creation. The final artifacts (1 per team) provided evidence of TD knowledge Creation.

The text-based data collected was analysed using deductive and inductive thematic analyses (as described in section 3.8.5) to extract evidence of the student experience about TD collaboration & knowledge creation. The artifacts produced were assessed for their contribution to TD knowledge creation by assessing their innovative quality and TD integration using the Transdisciplinary Integration Quality Scale (TIQS) analysis method (explained in Section 5.2.3.2).

Finally, the researcher's reflective journal containing observational and reflective notes was analysed using critical incident analysis (explained in 3.9.1) to indicate crucial change in understanding.

The results of the data collection and analysis are presented in the observe section 5.3.3 below.

5.3.2 Act - Iteration 5

5.3.2.1 Implementation

In this iteration, the collaborative dynamics observed during the summer internship environment (Iteration 3) were intentionally emulated by ensuring that all students received instruction collectively and worked together throughout the class period. To support this approach, recruitment focused on attracting qualified and motivated participants for the STEAM Design course, with the goal of achieving balanced representation from both the arts and engineering. Unlike previous iterations, this version of the course required all students to work collaboratively during the entire class session, fostering continuous interaction and shared learning across disciplines.

Recruitment strategies were informed by lessons learned from Iteration 1. An open call was issued to both faculties, inviting art and engineering students to participate in a single, fully integrated class environment designed to support transdisciplinary collaboration. Recruitment efforts included broad announcements within both faculties, as well as encouragement from art professors who promoted the course to their students. Applicants were asked to submit a statement of interest describing their motivations for joining the course, enabling the selection of participants most suited to this collaborative learning environment.

Iteration 5, the first fully multidisciplinary offering of the STEAM Design course, welcomed twelve students from the arts and twelve from engineering, reaching the course's maximum capacity. Students worked in multidisciplinary teams to conceive and design small-scale functional prototypes addressing an environmental issue of their choice. Each team selected its theme and medium in response to the guiding question: *"What is the most urgent environmental problem for you?"* The resulting artifacts are summarised in the *Observational Findings* section below.

At the end of the course, teams were scheduled to present their prototypes to prospective institutional partners interested in supporting summer internships during which students would develop full-scale versions of their projects for installation. However, COVID-19 restrictions came into effect in March 2020, requiring students to complete their projects through online collaboration. As a result, the planned client presentations had to be cancelled.

5.3.2.2 TD-SDT Components Studied

Teach-a-skill Tool to Establish Community of Practice

The *Community of Practice (CoP)* mechanism proved particularly effective during Iteration 3 (see Section 4.4). To accelerate the formation of a CoP within the shorter timeframe of a one-semester course, the *Teach-a-Skill* activity was introduced.

In this activity, each team member selected a skill related to their disciplinary background, personal expertise, or the environmental issue addressed in the project. Students then taught this skill to their teammates through short demonstrations or guided exercises. By sharing knowledge in this way, students moved beyond their disciplinary roles and began contributing expertise to the collective learning environment.

This activity helped establish conditions associated with communities of practice—mutual learning, knowledge sharing, and the gradual development of shared expertise. Through these exchanges, students began to recognise the diverse capabilities within their teams and developed a stronger sense of collaborative ownership of the project.

ITP Metrics for Reflexivity

To further support reflexivity, students completed the ITP Metrics personality assessment (described in Section 3.6.1). This tool had previously demonstrated value in encouraging reflective discussions about collaboration during Iteration 2 (see Section 4.3).

The assessment, which includes the Big Five personality test and a peer feedback system, was used not as a diagnostic instrument but as a reflective prompt. Students discussed their results within their teams, exploring how differences in working styles, communication preferences, and decision-making approaches might influence collaboration.

These conversations helped teams recognise cognitive and interpersonal diversity within the group, fostering epistemic humility and encouraging more intentional collaboration practices.

Open Challenge to Foster Ambiguity

To expose students to the productive role of ambiguity in design processes, this iteration introduced an open challenge format. Rather than providing a tightly specified brief, students were invited to define their own approach to a chosen environmental issue.

Within this framework, teams were given substantial freedom in both technical and artistic directions, allowing them to explore the issue using any medium, technique, or art form relevant to their concept. Only a small number of constraints were maintained to ensure feasibility within the course.

Design research has long recognised ambiguity as a generative condition that stimulates creativity, reframing, and iterative knowledge development (Cross, 2006; Dorst, 2019; Kolko, 2010; Lawson, 2006; Rittel & Webber, 1973). By reducing prescriptive constraints, the open challenge encouraged students to grapple with uncertain problem definitions and to explore multiple possible directions before converging on a solution.

Activating Transdisciplinary Cognitive Skills (TCS)

In this iteration, students were introduced to Henriksen's seven Transdisciplinary Cognitive Skills (TCS) through selected readings and guided activities. These skills—outlined in Section 2.5.4.1—describe cognitive processes shared across artistic, scientific, and design practices.

Attention was given to three skills considered especially relevant to the course objectives: perceiving, abstracting, and playing. The following activities were designed to provide experiential engagement with these modes of thinking.

Formal Analysis as a Tool for Perceiving

To develop students' perceptual awareness, the course introduced *formal analysis*, a method commonly used in art history and visual studies to examine the formal properties of artworks. Although familiar within artistic training, this approach was new to many engineering students.

Formal analysis focuses on the careful observation of elements such as form, colour, composition, texture, scale, and spatial relationships. By systematically examining these features, observers can describe and interpret how visual structures contribute to the meaning and experience of a work.

To support this exercise, students participated in a guided visit to a contemporary art exhibition at a nearby national fine art museum. During the visit, both art and engineering students practiced formal analysis of selected artworks under the guidance of a museum educator. Following the visit, each student produced a written formal analysis of an artwork of their choice.

This activity aimed to strengthen students' observational abilities and to cultivate attentiveness to visual and material qualities—skills associated with the TCS dimension of *perceiving*.

LEGO® Serious Play® for Abstracting and Playing

To encourage exploratory thinking and collaborative reflection, the *LEGO® Serious Play® (LSP)* method *(Lego, 2019)* was introduced. This facilitated activity invited interdisciplinary teams to construct physical models representing the environmental issue they had chosen to address.

Using a limited set of LEGO bricks and a constrained time frame, each team built a symbolic representation of their issue. Students then presented their models to the class using a structured storytelling format in which the model itself served as the language of explanation—for example: *"In the model, I see two groups of individuals separated by a tall wall…"*.

This approach encouraged participants to translate abstract ideas into metaphorical forms, stimulating reflection and dialogue within the group. The activity activated two of Henriksen's transdisciplinary cognitive skills: *abstracting*—the process of distilling the essential characteristics of a concept—and *playing*, which enables participants to explore ideas in a low-risk and imaginative manner. As Root-Bernstein & Root-Bernstein (2001) note, playful exploration can provide a powerful means of reframing problems and generating new perspectives.

Synthesis of Iteration Tools

Taken together, this iteration introduced several pedagogical interventions intended to expand the evolving components of the TD-SDT. These included the *Teach-a-Skill activity* to accelerate the formation of a Community of Practice, the *ITP Metrics assessment* to support reflexive awareness of collaboration dynamics, and an *open challenge format* designed to increase ambiguity within the design brief. In addition, three of Henriksen's Transdisciplinary Cognitive Skills—perceiving, abstracting, and playing—were activated through targeted activities. *Formal analysis* was used to cultivate perceptual attention, while *LEGO® Serious Play®* encouraged abstraction and playful exploration of complex issues. Together, these interventions provided opportunities to examine how different pedagogical conditions might contribute to transdisciplinary collaboration and knowledge creation.

5.3.3 Observe - Iteration 5

5.3.3.1 Overview Data Collected

By the end of this iteration, data were collected from five teams comprising 20 students**:** 7 from the arts and 13 from engineering, including 11 females and 9 males (Table 24). Individual-level data included 57 reflective journal entries (Blogs 1, 3, 4, and 5), which were collated into 16 individual reflective journals corresponding to the students who contributed entries. The reflective journal prompts are provided in APPENDIX O.

Table 24 Iteration 5 Data Collected

Iteration 5 - Data Collected													
Identification								Individual Data		Team Data			Researcher Data
Iteration	Teams	N Students	A	E	O	F	M	Journals	Collated Journals	Final Reports	Prototypes	Final Artifacts	Journal
5	1	4	2	2	0	2	2	14	4	1	3	1	
	2	5	2	3	0	2	3	19	5	1	2	1	
	3	4	1	3	0	3	1	8	2	1	2	1	
	4	3	1	2	0	1	2	7	3	1	3	2	
	5	4	1	3	0	3	1	9	2	1	2	1	
5	5	20	7	13	0	11	9	57	16	5	12	6	1

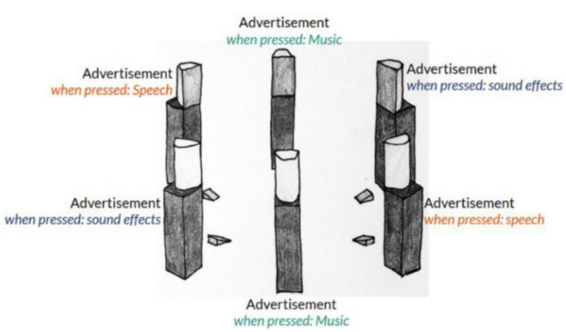
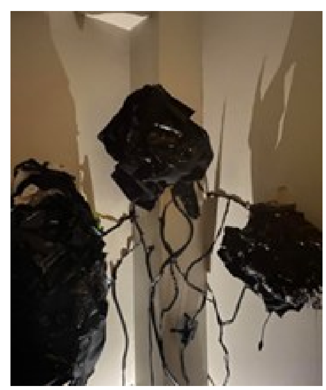
Team-level materials included five final reports, twelve intermediary prototypes, and six final artifacts. A summary description of the artifacts is presented in Section 5.3.3.2 (Artifacts), while detailed documentation of prototype evolution and final artifacts is provided in APPENDIX R. In addition, one researcher observation journal was collected.

Representative excerpts drawn from the reflective journals, final reports, and researcher observation notes are discussed in the Observational Findings (5.3.3.3). A summary of the final artifacts is presented in the following section.

5.3.3.2 Artifacts Produced

Together the five projects of Iteration 5 (Table 25) trace a continuum of students' environmental and social concerns. T1 *Noise Censorship* focuses on sound art to force viewers to confront their relationship to consumerist structures in society. T2 *The Creature* centres on pollution and the long-term effects of human pollution on the planet. T3 *Kinology* explores the disconnect humans feel between their actions and their impact on the environment. T4 *WHELD* investigates the end-of-life cycle of consumer objects through the reuse of recycled cardboard boxes. And T5 *Surveillance Tree* examines urban environments and their impact on mental well-being, specifically through the theme of hostile urban design and surveillance.

Table 25 Iteration 5 Final Artifacts

Team 1 – Noise Censorship	*Team 2 – The Creature*
	

Team 3 -Kinology 	*Team 4a – End of Life Cycle (video)*  *Video Link*
Team 4b - End of Life Cycle (Website)  *Website Link*	*Team 5 – Surveillance Tree* 

This was a summary description of the artifacts created in this iteration, a detailed description of the prototypes evolution and final artifact can be found in APPENDIX R.

5.3.3.3 Observational Findings

The 16 collated individual reflective journals, and 5 final reports collected were analysed to find evidence of impact of tools introduced in this iteration on TD Collaboration & TD Knowledge Creation.

Inductive Thematic Analysis – General Topics Discussed

Student Reflections General Topics

An inductive thematic analysis of student reflections and final reports revealed six recurring themes shaping how students experienced TD collaboration in practice: engagement with TD collaboration, the demanding nature of creative work, team dynamics and self-awareness, pedagogical structures and workload, adaptation to COVID-19 constraints, and broader environmental and social consciousness.

Across the dataset, students consistently described TD collaboration as both challenging and generative. Differences between artistic and engineering approaches initially produced tension—particularly around abstraction, emotional impact, and methodological rigor—but were increasingly reframed as complementary. As one engineering student explained, *“art students are able to think abstractly and are considered about how something makes a viewer feel… engineers will be able to take the creative and powerful ideas art students think of and try to figure out how to make it a reality” (I5 T1 Eng Male)*. An art student similarly described a shift in perception: *“I kind of had a realisation that they weren’t necessarily just engineers… that revelation really inspired me” (I5 T2 Art Female).* These accounts suggest that disciplinary friction functioned as a catalyst for perspective-taking rather than a barrier to collaboration, reflecting epistemic reflexivity and the emergence of a shared Community of Practice.

A second dominant theme concerns the iterative and often emotionally demanding nature of the creative process. Students emphasised that meaningful outcomes emerged through prolonged uncertainty, repeated failure, and conceptual reworking. Creation was framed as sustained labor rather than inspiration, with one student describing it as *“excruciatingly painful… about digging deeper into your own beliefs” (I5 T1 Art Female)*. Prototyping—especially at full scale—was frequently identified as a turning point, enabling teams to move from abstract ideas to embodied understanding: *“Getting to a 1:1 prototype… is huge… because of how much we are able to learn” (I5 T4 Eng Male)*. Several teams also struggled to articulate a clear conceptual thesis, noting that uncertainty about intent slowed convergence (I5 T4 Eng Male). These reflections align with the TD-SDT view that ambiguity is not a weakness but a necessary condition for transdisciplinary knowledge creation, with iteration and prototyping enabling shared understanding without premature closure.

Students also reflected extensively on team dynamics, personality, and self-awareness, often mediated through structured assessment tools. Personality metrics and peer feedback provided a shared language for discussing conflict, roles, and participation. While some responses expressed discomfort—*“Am I an overbearing control freak????” (I5 T1 Art Female)*—others highlighted the value of these tools for clarifying expectations and surfacing latent tensions. High agreeableness, for example, was seen as both a strength and a risk: *“if people disagree they may not bring it up which might lead to dissatisfaction in the long run” (I5 T2 Eng Male)*. These reflections highlight collaboration as an affective and relational practice, supporting the TD-SDT emphasis on relational infrastructure and epistemic humility.

A fourth theme focused on pedagogical structures and workload. Many students criticised the volume of written deliverables relative to hands-on making, often framing the course as overly administrative—*"Y'a trop de paperasse!!!!!!!" (I5 T1 Art Female)* . At the same time, students distinguished between administrative burden and instructional value, consistently praising targeted mentorship and expert intervention: *"his tutorial and methodical explanations… really helped Deer Squad understand what an Arduino does"(I5 T1 Eng Male)*. These critiques reflect second-order reflexivity, where students evaluated not only collaboration but also the pedagogical system enabling it.

The analysis also captures students' experiences of the extraordinary constraints imposed by the COVID-19 pandemic. Teams described rapid shifts to virtual collaboration, sometimes creatively maintaining cohesion through shared online spaces *"We have adapted our team dynamics to the social distancing and team members having to move back home …" (I5 T2 Eng Male)*, while redesigning projects for digital presentation. These adaptations were accompanied by affective strain, including exhaustion and demoralisation toward the end of term (I5 T5 Eng Female). At the same time, the pandemic intensified learning around resilience, flexibility, and the translation of physical concepts into digital forms, illustrating how boundary objects must be reconfigured across contexts and forcing problem reframing.

Finally, many reflections demonstrated sustained engagement with environmental and social concerns, particularly consumerism, surveillance, and ethical complicity. Students grappled with tensions between personal behaviour and critical intent, as illustrated by one admission: *"I felt like a hypocrite!… I don't have to be perfect for my art to be meaningful" (I5 T4 Art Female)*. Projects addressing urban surveillance, environmental degradation, and labor exploitation were framed as moral as well as technical inquiries (T3 Final Report; T5 Final Report). These reflections position STEAM collaboration as a site where ethical reflection, creative practice, and systems thinking intersect, with artistic practice functioning as symbolic infrastructure for societal sense-making.

Students' engagement with consumerism, surveillance, and ethical contradiction illustrates the role of artistic practice as *symbolic infrastructure*—enabling reflection on systemic relationships between self, society, and environment (seen in Section 2.5.1.4). Feelings of hypocrisy and moral tension are indicators of *deep epistemic reflexivity*, where knowledge creation is inseparable from ethical positioning. This expanded learning goals exceeded task completion and moved toward societal sense-making.

Together, the six inductive themes show strong alignment between students lived experiences and the TD-SDT core concepts. Students' accounts provide a grounded, practice-based lens on how communication, trust, reflexivity, and symbolic infrastructure shape TD collaboration and knowledge creation.

Researcher's Key Observational Notes

The researcher's reflective journal highlighted several *critical incidents* that shaped Iteration 5 and informed subsequent refinements of the TD-SDT. First, the design challenge was perceived as potentially *too open*, generating productive ambiguity for some students while initially overwhelming others, thereby foregrounding the need for scaffolding without prematurely constraining exploration. In contrast, *Lego® Serious Play (LSP)* emerged as a particularly effective intervention, enabling students to think abstractly, externalise ideas, and negotiate meaning across disciplines (Boundary Objects effect) within a playful, low-risk environment that reduced fear of failure and supported early sensemaking. Finally, the abrupt onset of COVID-19 constituted a major disruptive incident at towards the end of the course, forcing rapid adaptation in pedagogy, collaboration, and project outcomes, and revealing both the fragility and resilience of TD learning infrastructures under extreme constraints.

Deductive Thematic Analysis to Assess TD-Process for this Iteration

This section applies the deductive thematic analysis workflow defined in Section 5.2 to examine the performance level of each dimension of the TD-Process Assessment Framework in Iteration 5. Student reflective journals and team final reports were analysed using the structured TD Codebook (APPENDIX G), with deductive codes drawn from the TD Process Assessment dimensions (e.g., trust, mutual learning, conflict handling).

The coding procedure was applied consistently across teams, generating comparable sets of qualitative indicators for each concept/tool pair. These indicators were used to substantiate assessments of TD process quality and to interpret the contribution of specific TD-SDT tools. The frequency and distribution of supporting excerpts across teams were treated as indicative of the relative strength and salience of each concept/tool pair within teams and iteration.

The process and results of this deductive analysis are presented in the following section.

5.3.3.4 TD Process Assessment (TDP)

Following the TD Process Assessment methodology described in section 5.2, the qualitative indicators extracted through deductive thematic analysis (student quotes as evidence) were used to assess each TD Process Assessment Framework dimensions (C1–C7; K1–K6) for each of the 5 teams in Iteration 5. The resulting team-level and iteration-level assessments are presented in Table 26.

Understanding the TD Process Assessment Framework

The information contained in Table 26 is first discussed and interpreted, followed by a detailed explanation of how each section of the assessment was obtained.

Table 26 Iteration 5 TD Process Assessment Framework

I5 TD Process Assessment Framework					I5 TD Process Assessment				
				I5	T1	T2	T3	T4	T5
TD Process Quality – TD Collaboration			**TPQ Score**	**2.26**	**2.71**	**2.14**	**2.29**	**1.71**	**2.43**
	Collaborative Process	C1- Trust	L/M/H [0,3]	**2.60**	**3.00**	**3.00**	**2.00**	**2.00**	**3.00**
		C2- Communication		**2.00**	**3.00**	**2.00**	**2.00**	**1.00**	**2.00**
		C3- Mutual Learning		**2.60**	**3.00**	**3.00**	**3.00**	**2.00**	**2.00**
		C4- Conflict Handling (Friction)		**1.60**	**2.00**	**1.00**	**2.00**	**1.00**	**2.00**
		C5- Shared Problem Framing		**2.20**	**3.00**	**2.00**	**2.00**	**2.00**	**2.00**
	Reflexivity	C6- Equal Footing, Power Relationships & Fairness		**2.60**	**3.00**	**2.00**	**3.00**	**2.00**	**3.00**
		C7- Team Critical Self-Awareness		**2.20**	**2.00**	**2.00**	**2.00**	**2.00**	**3.00**
TD Integration Quality – TD Knowledge Creation (Tangible)			**TIQ Score**	**1.62**	**1.75**	**2.17**	**1.00**	**2.08**	**1.08**
	Artifacts Created	K1- Epistemic (Disciplinary) Grounding	L/M/H [0,3]	**1.70**	**1.75**	**2.25**	**1.00**	**2.25**	**1.25**
		K2- Integration Depth & Coherence		**1.55**	**1.50**	**2.25**	**1.00**	**2.00**	**1.00**
		K3- Advancement of Understanding (Novelty)		**1.60**	**2.00**	**2.00**	**1.00**	**2.00**	**1.00**
TD Societal Effects – TD Knowledge Creation (Intangible)			**TSE Score**	**2.20**	**3.00**	**2.00**	**2.00**	**2.00**	**2.00**
	Learning & Capacity Building of Participants	K4- Cognitive, Social & Practical Competencies	L/M/H [0,3]	**2.20**	**3.00**	**2.00**	**2.00**	**2.00**	**2.00**
	Societal Usefulness	K5- Salient, Credible, Legitimate, Actionable							
	Societal Impacts	K6- Policy & Practices Change							
TD Process Score [0,9] where: Low =[0,2]; Medium=[3,5]; High=[6,9]			**TD Process Score**	**6.07**	**7.46**	**6.31**	**5.29**	**5.79**	**5.51**
			L/M/H [0,9]	**H**	**H**	**H**	**M**	**M**	**M**

The TD Process Assessment Framework (Table 26) is composed of three interrelated sub-elements: *TD Process Quality* (to assess TD collaboration), *TD Integration Quality* (to assess TD knowledge creation—tangible outputs such as artifacts), and *TD Societal Effects* (to assess TD knowledge creation—intangible outcomes such as participant learning).

At the bottom of Table 26, the TD Process Score summarises the overall strength of TD collaboration and TD knowledge creation for each team, as well as the iteration-level average. Scores range from 0 to 9, where 0 <= low < 3, 3<= medium < 6, and 6 <= high <= 9

In Iteration 5, Teams 1 and 2 achieved high TD Process Scores (7.46 and 6.31), while Teams 3, 4, and 5 fell within the medium-high range (5.29, 5.79, and 5.51). The iteration-level average TD Process Score was 6.07, indicating overall high TD process quality.

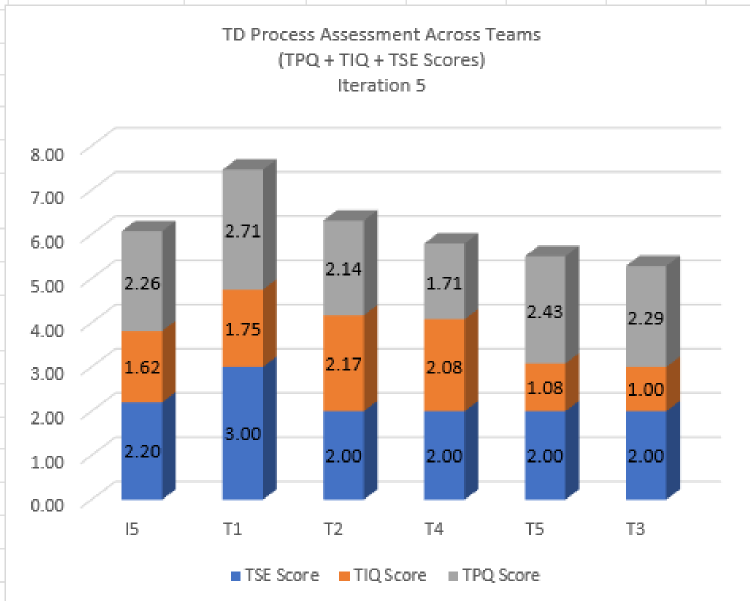


Figure 9 Iteration 5 TD Process Score = TPQ+TIQ+TSE Scores

As shown in Figure 9, each TD Process Score was calculated as the sum of three component scores: TD Process Quality (TPQ), TD Integration Quality (TIQ), and TD Societal Effects (TSE). Each component was scored on a scale from 0 to 3. The stacked bar chart in Figure 9 visually represents the relative contribution of each component to the overall TD Process Score and presents the teams in descending order of overall TD Process performance.

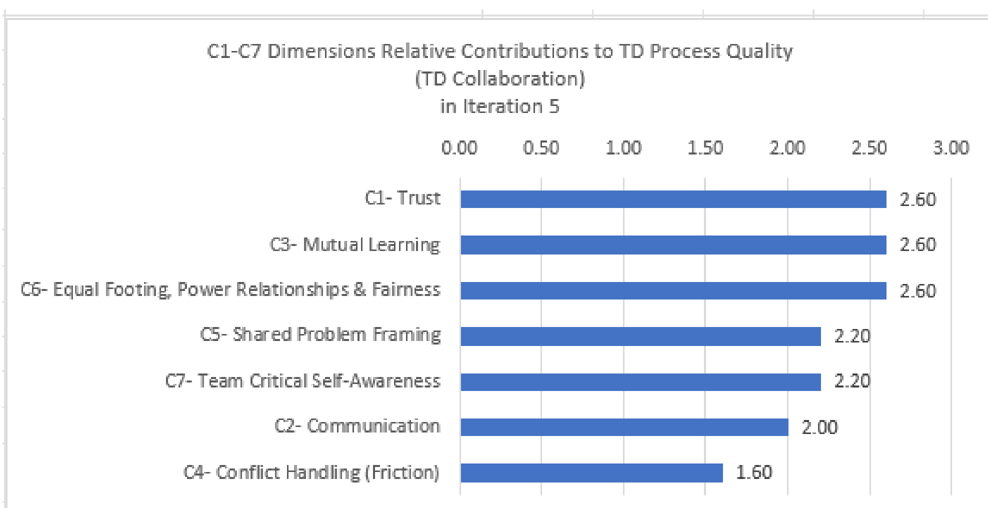


Figure 10 Iteration 5 Relative Contribution of C1-C7 to TD Process Quality

Figure 10 presents the relative contributions of the C1–C7 dimensions to the overall TD Process Quality (TD Collaboration) score in Iteration 5. Each iteration-level score represents the average of team-level scores which also ranges from 0 to 3.

In iteration 5, a high contribution (2.60) was observed for C1-Trust, C3-Mutual Learning and C6-Equal Footing, Power Relationship & Fairness. Medium contributions were observed for C5-Shared problem framing (2.20), C7- Team s Critical Self-Awareness (2.20) and C2-communication (2.00). And Low contribution (1.60) was observed for C4-Conflict handling.

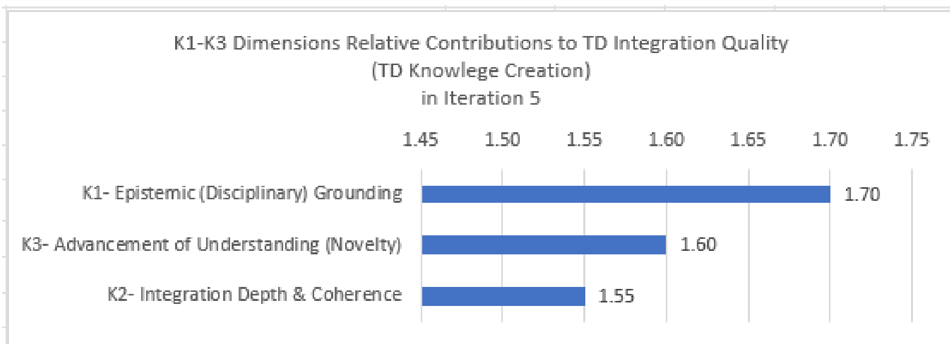


Figure 11 Iteration 5 Relative Contribution of K1-K3 to TD Integration Quality (TIQ)

Figure 11 presents the relative contributions of K1–K3 to the overall TD Integration Quality (of tangible TD Knowledge Creation, i.e. artifacts) score. As with TPQ, TIQ iteration-level score represents an average of team-level scores and ranges from 0 to 3.

In Iteration 5, all iteration-level scores are moderate with K1-Epistemic Grounding (1.70), K3-Novelty/Advancement of Understanding) (1.60), K2- Integration Depth and Coherence (1.55). And all three dimensions at the team-level fell within the lower-to-moderate range (1.00-2.25), indicating emerging but not yet deep integration across teams.

Finally, the TD Societal effects (TSE) of TD knowledge creation – intangible represent the learning and capacity building (K4) that happens during the collaboration.

In iteration 5, the assessed values are moderate to high (ranging from 2.0 to 3.00), representing a solid level of learning and capacity building.

Having looked at the significance of the TD Process Assessment Framework operationalised in Table 26), the following sections describe how each component was derived.

TD Process Quality (TPQ)

This section explains how TD Process Quality (TPQ) was assessed. Table 27 Iteration 5 TD Process Quality presents the assessed values for dimensions C1–C7 for each team in Iteration 5, along with the iteration-level averages. For example, Team 1 obtained a TPQ score of 2.71, which was calculated as the average of its C1–C7 dimension scores (e.g., C1 = 3.00; C2 = 3.00; … ;C7 = 2.0). The same calculation was applied to each team.

Iteration-level TPQ value was derived by averaging all team-level TPQ scores. The overall iteration-level TPQ score for Iteration 5 was 2.26. The average C1 score was 2.60; C2 = 2.00; C3 = 2.60; C4 = 1.60; and so forth.

Table 27 Iteration 5 TD Process Quality (excerpt from table 23)

I5 TD Process Assessment					I5 TD Process Assessment				
				I5	T1	T2	T3	T4	T5
TD Process Quality – TD Collaboration			**TPQ Score**	**2.26**	**2.71**	**2.14**	**2.29**	**1.71**	**2.43**
	Collaborative Process	C1- Trust	L/M/H [0,3]	**2.60**	**3.00**	**3.00**	**2.00**	**2.00**	**3.00**
		C2- Communication		**2.00**	**3.00**	**2.00**	**2.00**	**1.00**	**2.00**
		C3- Mutual Learning		**2.60**	**3.00**	**3.00**	**3.00**	**2.00**	**2.00**
		C4- Conflict Handling (Friction)		**1.60**	**2.00**	**1.00**	**2.00**	**1.00**	**2.00**
		C5- Shared Problem Framing		**2.20**	**3.00**	**2.00**	**2.00**	**2.00**	**2.00**
	Reflexivity	C6- Equal footing, Power relationships & fairness		**2.60**	**3.00**	**2.00**	**3.00**	**2.00**	**3.00**
		C7- Team Critical Self-Awareness		**2.20**	**2.00**	**2.00**	**2.00**	**2.00**	**3.00**

To obtain these values, deductive coding was conducted on students' reflective journals and final team reports. Extracted text segments (student quotations) were coded according to dimensions C1–C7 using the TD Process Codebook (APPENDIX G) aligned with the TD Process Assessment Framework (APPENDIX F).

This coding process produced team- and dimension-specific evidence sets consisting of illustrative quotations. These evidence sets functioned as qualitative indicators supporting rubric-based scoring of TD Process Quality (TPQ).

Table 28 presents an excerpt of the evidence sets used to support Team 1's assessed values. Table 29 provides an excerpt of the TPQ rubric used for scoring (see APPENDIX H for the full rubric).

Complete analyses and sources files can be found in the accompanying data repository.

Table 28 Iteration 5 TPQ Score Evidence Sets Excerpt (Team 1 Quotes) (Excerpt)

		Team 1: Deer Squad
Score	Letter	Quote
19	Sum	**Cluster A — TD Process Quality: Transdisciplinary Collaboration**
3	H	• **C1: Trust**
	3	◦ Candide (T1 S2) reflected on early group dynamics: "It's interesting to note how Trust and Contribution Equity are th
		◦ Navi (T1 S4) noted that the group felt safe: "all my group members respect what I have to say and are not judgment
		• "Trust and Contribution Equity are the highest scores out of all of them. I would definitely agree that in the beg
3	H	• **C2: Communication**
	4	◦ James (T1 S1) credited their success to clear exchange: "The primary thing that makes us such a good group is that v
		◦ The **Final Report** acknowledged that while backgrounds differed, they found value in the struggle: "communication c
		◦ Senka (T1 S3) noted the pressure to be clear: "you are constantly pushed by your teammates to take your thinking o
		• "Our team scored pretty high in terms of communication. I think the biggest takeaway we got from this was that we h
3	H	• **C3: Mutual Learning**
	3	◦ James (T1 S1) observed the benefit of merging perspectives: "engineers will able to take the creative and powerful i
		◦ Candide (T1 S2) acknowledged cross-disciplinary skill-sharing: "Senka's Teach a Skill on Isadora was instrumental in
		• "Senka's Teach a Skill on Isadora was **instrumental in my understanding of the node-based and 'output' logic**
2	M	• **C4: Conflict Handling (Friction)**
	2	◦ Navi (T1 S4) identified this as a personal contribution: "my ability to resolve conflicts will be useful when group argu
		◦ James (T1 S1) noted a preference for collaboration over tension: "I tend to always try to avoid disagreements by inte
3	H	• **C5: Shared Problem Framing**
	3	◦ The **Final Report** detailed the lengthy process: "We spent a **lot of time brainstorming**, discussing and reflecting on f
		◦ Senka (T1 S3) described the evolution of their topic: "Our project evolved from a very literal representation of consu
		• "We spent a lot of time brainstorming... **numerous attempts and projects ideas were thrown around** before v
3	H	• **C6: Equal Footing, Power & Fairness**
	2	◦ The **Final Report** emphasized balanced effort: "the **workload for each deliverable had been divided up evenly** based
		◦ Tasks were assigned based on expertise: "James and Navi worked on Arduino and pedals and connections while **Sen**
2	M	• **C7: Team Critical Self-Awareness**
	4	◦ James (T1 S1) recognized his own disciplinary bias: "I will really try to think of ideas with no limitations and try to re
		◦ Senka (T1 S3) reflected on her communication hurdles: "I've realized that while I am very much capable of thinking c
		◦ Candide (T1 S2) critiqued their internal management: "The one weaker score, Goal Progression, makes sense. Althou
		• "These assessments... provided great insight and gave me some things to ponder on, and paths towards self-i

Table 29 Rubric - TD Process Quality Assessment (Excerpt)

TD Process Quality Assessment Rubric			
C1 — Trust			
Score	**Level**	**Descriptor**	**Indicators (Observed Evidence)**
0	Absent	Lack of trust inhibits collaboration	Defensive behavior; reluctance to share ideas or uncertainty
1	Emerging	Conditional or uneven trust	Participation varies by role, discipline, or confidence
2	Developing	Stable trust supports collaboration	Open discussion; respectful feedback and critique
3	Established	High trust enables risk-taking	Willingness to share unfinished ideas and admit uncertainty
C2 — Communication			
Score	**Level**	**Descriptor**	**Indicators (Observed Evidence)**
0	Absent	Communication breakdowns	Misunderstandings; parallel work without alignment
1	Emerging	Basic information exchange	Updates shared but meanings remain siloed
2	Developing	Dialogic communication	Active listening; clarification across disciplines
3	Established	Integrative communication	Shared language enabling collective sense-making

Table 30 presents the distribution of the 200 student quotations used to assess TD Process Quality in Iteration 5, disaggregated by team and dimension.

Table 30 Iteration 5 Number and Distribution of Student Quotes to Assess TD Process

I5 TD Process Assessment Framework (Quotes)				I5	I5 Number of Quotes Used for Assessment				
				I5	T1	T2	T3	T4	T5
TD Process Quality – TD Collaboration			**TPQ n Quotes**	**114**	**21**	**26**	**20**	**22**	**25**
	Collaborative Process	C1- Trust	n Quotes	16	3	4	2	3	4
		C2- Communication		18	4	4	3	4	3
		C3- Mutual Learning		18	3	5	4	2	4
		C4- Conflict Handling (Friction)		16	2	4	2	4	4
		C5- Shared Problem Framing		17	3	3	4	4	3
	Reflexivity	C6- Equal Footing, Power Relationships & Fairness		12	2	3	2	2	3
		C7- Team Critical Self-Awareness		17	4	3	3	3	4
TD Integration Quality – TD Knowledge Creation (Tangible)			**TIQ n Quotes**	**47**	**10**	**10**	**9**	**9**	**9**
	Artifacts Created	K1- Epistemic (Disciplinary) Grounding	n Quotes	20	4	4	4	4	4
		K2- Integration Depth & Coherence		15	3	3	3	3	3
		K3- Advancement of Understanding (Novelty)		12	3	3	2	2	2
TD Societal Effects – TD Knowledge Creation (Intangible)			**TSE n Quotes**	**39**	**9**	**9**	**6**	**6**	**9**
	Learning & Capacity Building of Participants	K4- Cognitive, Social & Practical Competencies	n Quotes	15	4	3	2	2	4
	Societal Usefulness	K5- Salient, Credible, Legitimate, Actionable		15	3	4	2	3	3
	Societal Impacts	K6- Policy & Practices Change		9	2	2	2	1	2
			TD Process Total Quotes	**200**	**40**	**45**	**35**	**37**	**43**

TD Integration Quality (TIQ)

The TIQ Score reflects the integration quality of each team's final artifact. Triangulation was used on TIQ since it can be assessed using two complementary methods:

1. **$TIQ_{artifact}$ Scoring** – evaluation of the final artifacts themselves
2. **TIQ_{quote} Scoring** – deductive analysis of student quotations

Both methods assessed integration quality across dimensions: K1 – Epistemic Grounding, K2 – Integration Depth and Coherence, and K3 – Advancement of Understanding / Novelty. Scores were assigned on a 0–3 scale following the TIQS methodology described in Section 5.2.3.2. Because $TIQ_{artifact}$ Scoring directly evaluates the artifact and provides a richer evidentiary basis, it carries greater weight in the overall TIQ analysis and serves as the primary TIQ measure. TIQ_{quotes} Scoring is used as a triangulation mechanism to support and validate the $TIQ_{artifact}$ Scores.

TIQ_{quote} Scoring

TIQ_{quote} Scoring followed the same deductive coding procedure used for TPQ. Student quotations were assessed using the *K-Dimension rubrics* (APPENDIX I,APPENDIX J,APPENDIX K). The extracted quotations provided qualitative evidence of the perceived disciplinary grounding in each discipline involved (Table 31), the depth of integration achieved by the team and epistemic advancement or novelty obtained by the team during the TD collaboration

Table 31 Iteration 5 TD Integration Quality Scoring (quotes)

TIQ_{quote} Scoring					
I5	T1	T2	T3	T4	T5
1.40	2.00	1.67	0.67	1.67	1.00
1.80	2.00	2.00	1.00	2.00	2.00
1.60	2.00	2.00	1.00	2.00	1.00
0.80	2.00	1.00	0.00	1.00	0.00

$TIQ_{artifact}$ Scoring

Table 32 and Table 33 present the assessed values for each K-dimension and the resulting $TIQ_{artifact}$ scores. Using *K-Dimension rubrics* (APPENDIX I,APPENDIX J,APPENDIX K), each K-dimension value was assessed. *K1* (Epistemic or Disciplinary Grounding) was evaluated separately for each participating discipline and then averaged; *K2* and *K3* were assessed at the artifact level using the corresponding rubric. Together, these scores characterise the degree to which artifacts achieved meaningful disciplinary synthesis.

Table 32 Iteration 5 TD Integration Quality (artifact)

TD Integration Quality – TD Knowledge Creation (Tangible)			TIQ Score	1.62	1.75	2.17	1.00	2.08	1.08
	Artifacts Created	K1- Epistemic (Disciplinary) Grounding	L/M/H [0,3]	1.70	1.75	2.25	1.00	2.25	1.25
		K2- Integration Depth & Coherence		1.55	1.50	2.25	1.00	2.00	1.00
		K3- Advancement of Understanding (Novelty)		1.60	2.00	2.00	1.00	2.00	1.00

Table 33 Iteration 5 TIQartifact Score Calculations

I5 TD Integration Quality									
Prototype Phase	Iteration	Team	Evaluator	Discipline Grounding Engineering	Discipline Grounding Art	Average Disciplinary Grounding	Integration Depth & Coherence	Advancement - Innovation - Novelty	Integration Quality Score
1-3	5	1-5		K1 [0.3]	K1 [0.3]	K1 [0.3]	K2 [0.3]	K3 [0.3]	TIQS [0.3]
Prototype 1	5	1	C	N/A	N/A	N/A	N/A	N/A	N/A
Prototype 2	5	1	C	0	1	0.50	0.75	0	0.42
Prototype 3	5	1	C	2	1.5	1.75	1.50	2	1.75
Prototype 1	5	2	C	N/A	N/A	N/A	N/A	N/A	N/A
Prototype 2	5	2	C	1.5	1	1.25	1.25	1	1.17
Prototype 3	5	2	C	2.5	2	2.25	2.25	2	2.17
Prototype 1	5	3	C	N/A	N/A	N/A	N/A	N/A	N/A
Prototype 2	5	3	C	0	2	1.00	1.50	1	1.17
Prototype 3	5	3	C	0	2	1.00	1.00	1	1.00
Prototype 1	5	4	C	N/A	N/A	N/A	N/A	N/A	N/A
Prototype 2	5	4	C	2	1.5	1.75	1.25	2	1.67
Prototype 3	5	4	C	2	2.5	2.25	2.00	2	2.08
Prototype 1	5	5	C	N/A	N/A	N/A	N/A	N/A	N/A
Prototype 2	5	5	C	1	1	1.00	0.75	1	0.92
Prototype 3	5	5	C	1	1.5	1.25	1.00	1	1.08
				N/A : indicate that the first prototypes were not assessed					

Figure 12 and Figure 13 illustrate TIQS evolution of team prototypes:

- Figure 12 shows TIQS progression across prototype stages (1–3) for each team.
- Figure 13 shows TIQS evolution within each team across prototype development.

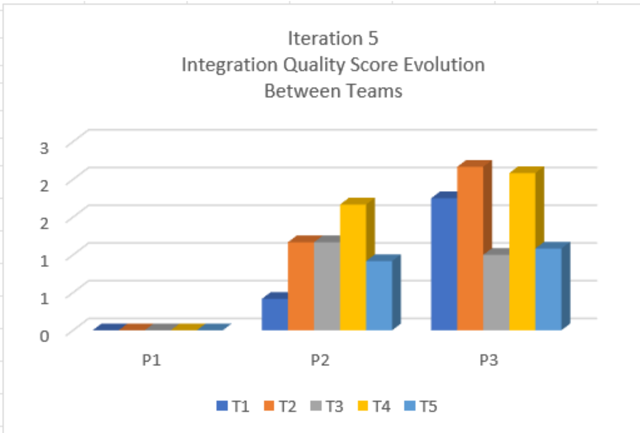


Figure 12 Iteration 5 TIQS Evolution Between Teams

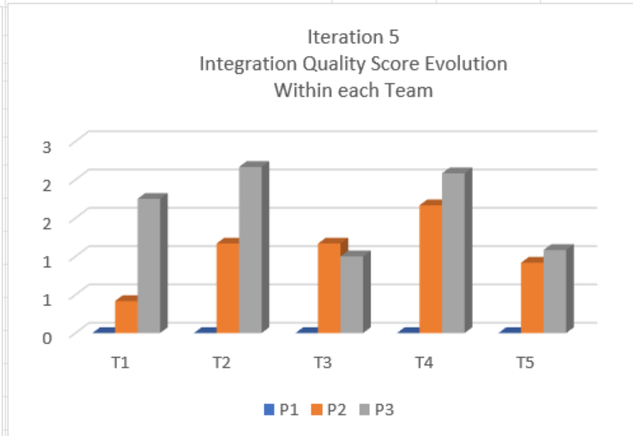


Figure 13 Iteration 5 TIQS Evolution Within Each Team

TIQ Scoring Triangulation

Table 34 shows the K1, K2, K3 values obtained through both methods. The key differences are highlighted in dark grey in TIQ_{quotes} scoring appear in the K3 assessed values. The examination of the quotes extracted confirmed limited information from the student quotes on K3, assessing the artifact advancement of understanding for the disciplines involved is an assessment type not expected from students. So K3 in TIQ_{quotes} scoring cannot be expected to be as acute as K3 in $TIQ_{artifact}$.

Table 34 Iteration 5 Variance Between TIQ artifact & TIQ quotes

	$TIQ_{artifact}$ Scoring					
	I5	T1	T2	T3	T4	T5
	1.62	1.75	2.17	1.00	2.08	1.08
K1	1.70	1.75	2.25	1.00	2.25	1.25
K2	1.55	1.50	2.25	1.00	2.00	1.00
K3	1.60	2.00	2.00	1.00	2.00	1.00
	TIQ_{quote} Scoring					
	I5	T1	T2	T3	T4	T5
	1.40	2.00	1.67	0.67	1.67	1.00
K1	1.80	2.00	2.00	1.00	2.00	2.00
K2	1.60	2.00	2.00	1.00	2.00	1.00
K3	0.80	2.00	1.00	0.00	1.00	0.00
	Score Variance					
	0.22	-0.25	0.50	0.33	0.41	0.08

The triangulation of TIQ scoring strengthened the values obtained and $TIQ_{artifact}$ values are the resulting value presented in Table 34 above.

TD Societal Effects (TSE)

The TD Societal Effects (TSE) score was assessed using the same 0–3 scale applied to K4–K6 dimensions.

Consistent with the methodological constraints described in Section 5.2, only K4 (Learning and Capacity Building) was empirically assessed in Iteration 5 using rubric K4 assessment grid (APPENDIX L). Dimensions K5 and K6 were conceptually retained but not evaluated in this academic context. The resulting scores are presented in Table 35.

Table 35 Iteration 5 TD Societal Effects

TD Societal Effects – TD Knowledge Creation (Intangible)			TSE Score	2.20	3.00	2.00	2.00	2.00	2.00
	Learning & Capacity Building of Participants	K4- Cognitive, Social & Practical Competencies	L/M/H [0,3]	2.20	3.00	2.00	2.00	2.00	2.00
	Societal Usefulness	K5- Salient, Credible, Legitimate, Actionable							
	Societal Impacts	K6- Policy & Practices Change							

This completes the TD Process Assessment for Iteration 5. Next section analyses tool contribution.

5.3.3.5 TD-SDT Tool Contribution Assessment

The assessment of TD-SDT concept–tool contributions to TD collaboration and TD knowledge creation draws on the TD Process Assessment dimensions theoretically expected to be activated as explained in Sections 2.6 and 5.2.4.

Deductive Thematic Analysis for each TD-SDT Tool

This section applies the deductive thematic analysis workflow defined in Section 5.2 to examine the contribution of each TD-SDT concept/tool pair implemented in Iteration 5.

Table 36 summarises the results of the deductive analysis (i.e. number of relevant student quotes extracted) done for the tools involved in Iteration 5.

Table 36 Iteration 5 Deductive Analysis of TD-SDT Concept/Tool Pairs

TD-SDT Components Introduced in I5		Number of Quotes per Team					Total
Concept	**Tool**	**T1**	**T2**	**T3**	**T4**	**T5**	**I5**
Mutual Learning	Teach-a-Skill (CoP)	8	11	1	1	6	27
Ambiguity	Open Challenge	8	6	0	2	1	17
TCS Perceiving	Formal Analysis	8	2	4	0	0	14
TCS Abstracting + Playing	Lego Serious Play	8	4	9	5	1	27
Reflexivity	ITP Metrics	17	12	5	7	9	50
Boundary Mediation	Boundary Object- LSP Model	4	1	1	1	0	7
Total Number of Quotes		53	36	20	16	17	142

A complete list of extracted quotes is available in the accompanying data repository.

Key excerpts supporting the interpretation of quotes extracted are presented in the Reflect section (Section 5.3.4). Evidence from student quotes regarding tool contributions is used to triangulate the quantitative assessment presented in the following section.

Assessment of TD-SDT Concept/Tool Pairs

Concept/tool pairs implemented in this iteration, along with their mapped TD Process dimensions, are listed in Table 37 (complete mapping presented in APPENDIX L).

Table 37 Iteration 5 Concept/Tool Pairs Mapping

TD-SDT Components Introduced in I5		TD Process Framework Mapping	
Concept	**Tool**	**TD Collaboration**	**TD Knowledge Creation**
Mutual Learning	Teach-a-Skill (CoP)	C3, C2, C6, C5	K4 (strong), K1, K2
Ambiguity	Open Challenge	C5, C4, C7	K3 (strong), K2, K4
TCS Perceiving	Formal Analysis	C2, C7	K1 (strong), K2
TCS Abstracting + Playing	Lego Serious Play	C2, C4, C6	K2 & K4 (strong), K3
Reflexivity	ITP Metrics	C7, C6	K1 (strong), K2, K4
Boundary Mediation	Boundary Object	C2, C5	K2 (strong), K1, K3

At the team level, tool contribution was assessed by aggregating the TD Process Assessment scores associated with the dimensions activated by a given concept–tool pair.

Table 38 presents the resulting concept/tool contribution profiles. The Iteration 5 averaged values of each TD Process Assessment Dimensions (C1-C7 & K1-K6) appear in the first column. The next 6 columns present the reported values for each tool in iteration 5.

The top 2 tools with high contributions to TD Process in Iteration 5 were Reflexivity – ITP Metrics (6.23), and Mutual Learning – Teach-a-Skill-CoP (6.18). The next 2 very close with medium-high assessed values were TCS Abstracting & Playing – Lego Serious Play (LSP) (5.84) and Ambiguity – Open Challenge (5.78). And the last 2 with low-medium impact were TCS Perceiving – Formal Analysis (3.73) and Boundary Mediating – Boundary Objects (3.72).

Table 38 Iteration 5 TD SDT Tool Assessment

I5 TD Process Assessment Framework			I5	Iteration 5 - Tool Assessment					
			Average	Mutual Learn - TAS	Ambiguity - OC	Perceiving - FA	Abs + Play - LSP	Reflexivity - ITPM	B.Mediation - BO
TD Process Quality – TD Collaboration		**TPQ Score**	**2.26**	**2.35**	**2.00**	**2.10**	**2.07**	**2.40**	**2.10**
Collaborative Process	C1- Trust	L/M/H [0,3]	2.60						
	C2- Communication		2.00	2.00		2.00	2.00		2.00
	C3- Mutual Learning		2.60	2.60					
	C4- Conflict Handling (Friction)		1.60		1.60		1.60		
	C5- Shared Problem Framing		2.20	2.20	2.20				2.20
Reflexivity	C6- Equal Footing, Power Relationships & Fairness		2.60	2.60			2.60	2.60	
	C7- Team Critical Self-Awareness		2.20		2.20	2.20		2.20	
TD Integration Quality – TD Knowledge Creation (Tangible)		**TIQ Score**	**1.62**	**1.63**	**1.58**	**1.63**	**1.58**	**1.63**	**1.62**
Artifacts Created	K1- Epistemic (Disciplinary) Grounding	L/M/H [0,3]	1.70	1.70		1.70		1.70	1.70
	K2- Integration Depth & Coherence		1.55	1.55	1.55	1.55	1.55	1.55	1.55
	K3- Advancement of Understanding (Novelty)		1.60		1.60		1.60		1.60
TD Societal Effects – TD Knowledge Creation (Intangible)		**TSE Score**	**2.20**	**2.20**	**2.20**	**0.00**	**2.20**	**2.20**	**0.00**
Learning & Capacity Building of Participants	K4- Cognitive, Social & Practical Competencies	L/M/H [0,3]	2.20	2.20	2.20	0.00	2.20	2.20	0.00
Societal Usefulness	K5- Salient, Credible, Legitimate, Actionable		0.00						
Societal Impacts	K6- Policy & Practices Change		0.00						
TD Process Score [0,9] where: Low =[0,2]; Medium=[3,5]; High=[6,9]		**TD Process Score**	**6.07**	**6.18**	**5.78**	**3.73**	**5.84**	**6.23**	**3.72**
		L/M/H [0,9]	**H**	**H**	**M**	**M**	**M**	**H**	**M**

Figure 14 shows graphically how each specific concept/tools contributed in TPQ, TIQ and TSE towards the TD Process in this iteration.

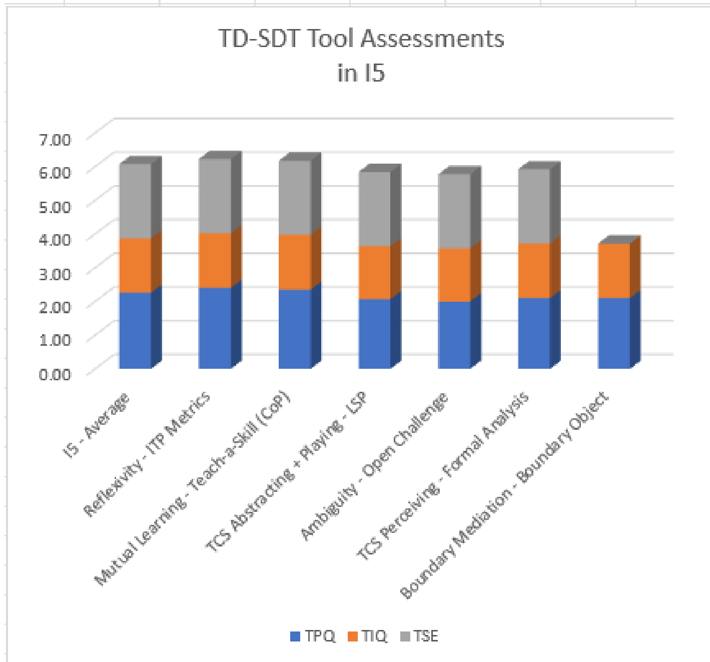


Figure 14 Iteration 5 TD-SDT Tools Assessment

Contrary to initial expectations, the tool assessment analysis led to very similar assessment scores for most tools, all contributing similarly toward the TD Process in this iteration.

5.3.3.6 Observe - Synthesis

The TD Process Assessment results—triangulated across rubric-based scores, artifact analysis, and qualitative evidence from student reflections and reports—indicate that Iteration 5 largely achieved its core objectives: fostering sustained transdisciplinary collaboration, supporting meaningful knowledge integration through making, and cultivating reflexive awareness of team dynamics and learning processes. Medium-to-high TD Process scores across teams reflect a productive balance between emerging trust and constructive friction. Particularly strong contributions were observed in mutual learning practices, reflexive self-awareness, and conflict engagement, where differences were actively negotiated rather than suppressed.

At the same time, variability across dimensions and tools highlights important boundary conditions—especially around conceptual convergence, workload management, and the emotional demands of prolonged ambiguity—that shaped how collaboration unfolded in practice. These patterns suggest that although Iteration 5 provided a robust foundation for transdisciplinary work, its effectiveness depended on how teams navigated uncertainty, iterative experimentation, and interpersonal dynamics.

The following *Reflect* section examines these dynamics in greater depth through selected student accounts. Participants' reflections are used to contextualise and interpret the triangulated assessment findings.

5.3.4 Reflect - Iteration 5

5.3.4.1 Key Insights

Building on the deductive and inductive analyses presented in the *Observe* section, this subsection synthesises key insights from Iteration 5 by examining how specific TD-SDT concept–tool pairings shaped transdisciplinary collaboration and knowledge creation in practice. The analysis focuses on six interrelated pairings—*Mutual Learning–Teach-a-Skill (CoP); Ambiguity–Open Challenge; TCS Perceiving–Formal Analysis; TCS Abstracting & Playing–Lego® Serious Play; Reflexivity–ITP Metrics; and Boundary Mediation–Boundary Objects*—and traces how they collectively supported social alignment, epistemic negotiation, and integrative sense-making across teams.

Mutual Learning - Teach-a-Skill (CoP)

Across Iteration 5, student reflections consistently describe the emergence of a *community of practice (CoP)* grounded in mutual learning, reciprocal skill exchange, and growing awareness of the social and affective dimensions of collaboration. Expertise was no longer framed as fixed or discipline-bound, but rather as relational and distributed across the team. As one student observed, *"this is the beauty of this class though, that people know things you don't, vice versa, and then we come together to create things we couldn't without each other"* (I5 T2 Art Female). This shift reflects a transition from individual competence toward collective capability.

Disciplinary differences were increasingly perceived as complementary rather than hierarchical. Engineering students articulated how artistic thinking expanded conceptual possibilities (what could be imagined), while art students acknowledged the structuring role of technical reasoning. One participant observed that *"art students are able to think abstractly and are concerned about how something makes a viewer feel… engineers will [then] take the creative and powerful ideas art students think of and try to figure out how to make them a reality"* (I5 T1 Eng Male). Peer-led teaching became an important site of epistemic translation, with students attributing conceptual breakthroughs to teammates' contributions: *"(My teammate's) teach-a-skill on Isadora was* *instrumental in my understanding of the node-based and 'output' logic also present in TouchDesigner"* (I5 T1 Art Female).

Importantly, these exchanges disrupted reductive disciplinary stereotypes. One student described a pivotal reframing moment: *"I kind of had a realisation that they weren't necessarily just engineers… They were both people who had experience in the artistic world and had really interesting things to say about it"* (I5 T2 Art Female). Such reflections signal the social learning dimension of the CoP, where trust and curiosity enabled recognition of hybrid identities and shared values. Students frequently expressed appreciation for this collaborative environment: *"I am grateful that I had the chance to participate in an inter-disciplinary environment such as this"* (I5 T2 Art Female).

The *Teach-a-Skill* structure formalised this community by legitimising students as knowledge holders. Learning occurred both informally—through spontaneous explanations—and through structured sessions. Students described how guidance accelerated collective progress: *"Guillaume was brought in to guide us… [which] really allowed us as a group to progress in our project"* (I5 T1 Eng Male). Others emphasised peer scaffolding: *"I also asked (my teammate) to explain what our specific Arduino does… (my other teammate) also recommended Codecademy to me, so I've been teaching myself Python!"* (I5 T2 Art Female).

Many students framed learning as an ongoing responsibility: *"I will make it a personal goal of mine to learn as much as I can from my teammates… and to potentially adopt some of their problem-solving strategies"* (I5 T5 Eng Female). Hands-on collaboration was frequently contrasted with traditional instruction: *"I believe working with others and working 'hands-on' has taught me much more than any lectures"* (I5 T3 Eng Female).

Beyond technical learning, students highlighted emotional and relational outcomes. Shared critique and collective challenges fostered empathy—*"this class has helped me develop greater empathy and a better ability to consider other people's perspectives"* (I5 T5 Eng Female)—as well as cross-disciplinary friendships: *"This class has allowed me to make friends with people I probably wouldn't have under normal circumstances"* (I5 T2 Art Female).

Finally, several teams connected their internal collaboration to broader societal impact, articulating goals for audience engagement: collaboration to broader *external societal impact*, articulating goals for audience impact: *"the viewer should feel a sense of unease"* (I5 T2 Final

Report) or prompting reflection on production cycles (I5 T4 Final Report). This outward orientation reinforced the perceived value of transdisciplinary education itself: *"I hope this class continues for years to come, because interdisciplinary opportunities like these are crucial"* (I5 T1 Art Female).

Ambiguity and Open Challenge - A Productive and Destabilising Force

Ambiguity emerged as one of the most formative conditions of Iteration 5. Students' experiences trace a clear *arc of ambiguity*— from early disorientation, through sustained conceptual uncertainty, toward gradual clarity achieved through iteration, feedback, and negotiation. In this sense, ambiguity functioned simultaneously as a creative catalyst and a destabilising force.

At the outset, open-ended parameters generated uncertainty and anxiety. One student reflected, *"I have never been in a course that is so open-ended, it's like an existential question—any answer fits, but what answer is most appropriate?"* (I5 T2 Eng Male). Another noted, *"At the start, I was unsure of what I'd end up doing in this class, as I don't have much knowledge of engineering, or making art that actually does things."* (I5 T2 Art Female).

As projects progressed, teams sometimes struggled to converge conceptually and articulate a stable intent—for example, *"I haven't been able to provide a concise thesis statement about our project yet…"* (I5 T4 Eng Male) and *"Our team lacked a clear purpose…"* (I5 T1 Art Female). Rather than signalling failure, such moments reflect characteristic phases of transdisciplinary boundary engagement, where differences in language, criteria, and practice become resources for reframing. Integration rarely emerges immediately; instead, it develops through iterative negotiation across epistemic cultures.

External feedback played a decisive role in transforming ambiguity into direction. One team noted, *"Having feedback from the class almost universally in favour of the all-black version clarified the issue for the group."* (I5 T2 Eng Male). Another reflected, "The feedback we received from our professors and classmates highlighted that this concept was lacking in several senses. First, it was underwhelming, and guest professor suggested that the effect of entrapment we were attempting to convey would not be felt in the final piece, a sentiment echoed by other individuals. *Retrospectively, I agree that it indeed was [underwhelming]."* (I5 T1 Art Female). These moments of rupture enabled convergence through collective re-framing.

At the individual level, ambiguity also followed a developmental arc. An early reflection—*"As of now, we don't know what we want to do our project on"* (Week 3)—later gave way to confidence:

“At this point, I am feeling a lot more confident…” (Week 7) (I5 T2 Art Female). This progression illustrates how uncertainty, when supported by peer collaboration and reflection, fostered epistemic resilience.

Overall, ambiguity operated as a structuring condition of the design process rather than a temporary obstacle to be resolved. Across teams, progress did not result from the reduction of uncertainty, but from the capacity to remain engaged within it. Moments of disorientation, stalled convergence, and critical feedback functioned as integral phases through which shared understanding was gradually constructed.

Within this context, ambiguity shaped both the trajectory of collaboration and the development of project outcomes. Teams that sustained engagement with uncertainty, supported by iteration, feedback, and negotiation, were able to move from diffuse exploration toward more coherent propositions. At the same time, the destabilising effects of ambiguity—manifested in confusion, tension, and difficulty articulating intent—required ongoing scaffolding to remain productive.

Taken together, these observations indicate that ambiguity is not simply a feature of open-ended design challenges, but a central condition through which transdisciplinary collaboration unfolds. Its productive potential depends on the extent to which it is actively supported, negotiated, and sustained within the learning environment.

Formal Analysis as a Perceiving Tool

Formal analysis was introduced to strengthen *observational capacity—perceiving*—one of Henriksen’s transdisciplinary cognitive skills. Although students did not always explicitly frame the assignment as training observation, their reflections indicate sustained attentiveness, visual scrutiny, and interpretive precision.

Students associated the task with attentiveness and detail: *“I think a lot of art is paying attention.”* (I5 T2 Eng Male); *“I like to pay attention to detail in this drawing…”* (I5 T1 Eng Male). Others recognised its unfamiliar demands: *“An artistic analysis is something completely out of my realm, but I welcomed the challenge with open arms.”* (I5 T3 Eng Male).

For many engineering students, the assignment represented a significant epistemic shift. Several described the steep learning curve and their reliance on peers with artistic training: *“One useful tool that is available for me to help improve on this weakness, is my art student groupmates who have done hundreds of papers…”* (I5 T3 Eng Male). Despite logistical challenges associated with the museum visit, students highlighted the value of the experience as a cultural and perceptual learning opportunity: *"The trip to the National Gallery of Canada was amazing…"* (I5 T1 Art Female).

In this sense, formal analysis functioned as a *productive friction point*, temporarily destabilising disciplinary habits while expanding students' observational, interpretive, and aesthetic capacities—skills essential for transdisciplinary sense-making.

Lego® Serious Play as an Abstracting and Playing Tool

Lego® Serious Play (LSP) was introduced to cultivate the transdisciplinary cognitive skills of abstracting and playing. Students' reflections indicate that the activity disrupted habitual modes of thinking, surfaced disciplinary assumptions, and enabled symbolic engagement with complex issues.

Participants frequently described the exercise as pushing them beyond their habitual approaches: *"it forces you to step out of your comfort zone and consider aspects of creation that you otherwise may not have stumbled upon.*" (I5 T1 Art Female). Some also recognised their initial tendency to prioritise structural form over conceptual meaning: *"I was most concerned with making the Lego structure a structure rather than a concept or idea…"* (I5 T3 Eng Female).

Students noted the plurality of interpretations that emerged during the exercise. One participant observed *"the amount of different ideas that could formulate in a fairly short period of time …"* (I5 T1 Art Female). Another reflected, "… *Seeing others' creations opened my mind to the use of different techniques… I saw that there were many other ways of going about the given instructions."* (I5 T3 Eng Female) Through this multiplicity, students began to recognise the legitimacy of multiple design pathways emerging from the same prompt and materials.

LSP also supported thematic convergence. Several teams reported that their project themes emerged directly from insights generated during the workshop. As one team noted, *"This theme arose in the Lego Serious Play workshop."* (I5 T1 Final Report). The models provided a concrete starting point for symbolically representing complex issues such as overconsumption, fast fashion, and broader environmental concerns. Teams also extended LSP-inspired approaches into later stages of divergence, discussion, and collaborative exploration.

The playful nature of the activity also fostered engagement and trust: "The class was innovative in bringing the student and their creative mind together... I've learned a lot from my teammates, which helps to create positive relationships for us, and it consolidates us as a group for the further project that we will face in the future" (I5 T2 Eng Male). It also supported mutual understanding of values and perspectives: *"After using Lego Serious Play to develop ways of communicating through the work... we came to understand what issues and concepts were important to each team member"* (I5 T2 Final Report)

Overall, LSP encouraged students to move beyond technical rigidity toward more open-ended conceptual exploration. *"The Lego activity… was really fun…"* (I5 T2 Art Female). As one participant reflected, *"What is crucial to this process... is uninhibited thinking. Actively, we must let go of the fear of mediocre ideas and allow ourselves to experience the exquisite, excruciating pain of thinking".* (I5 T1 Art Female)

Taken together, these observations indicate that LSP functioned as a low-stakes, generative environment that supported abstraction, multiplicity of interpretation, and early shared understanding. By enabling students to externalise ideas through symbolic forms and engage playfully with uncertainty, the activity contributed to the initial alignment of team perspectives and the emergence of project directions.

ITP Metrics as a Reflexivity Tool

ITP Metrics functioned as a reflexive diagnostic tool that surfaced tacit dynamics related to trust, conflict, and team contribution. Students' reflections reveal moments of critical self-examination—for example, *"Am I an overbearing control freak????"* (I5 T1 Art Female) —as well as team-level renegotiations of roles and responsibilities: *"we had to make our roles more clear…"* (I5 T1 Art Female).

Importantly, several students demonstrated *second-order reflexivity* by critically reflecting on the tool itself. One participant cautioned that their team's high '*agreeableness'* (according to ITP Metrics Big Five personality test, section 3.6.1) within a team might suppress dissent: *"if people disagree, they may not bring it up which might lead to dissatisfaction in the long run"* (I5 T2 Eng Male). Such reflections indicate an awareness of the limits of personality frameworks and highlight the need for ongoing dialogue rather than fixed categorisation.

Within the TD-SDT context, ITP Metrics therefore functioned less as a classificatory instrument and more as a *conversation catalyst*, enabling teams to surface relational dynamics and negotiate collaboration practices more consciously. By making interpersonal differences visible and discussable, the tool contributed to the development of trust, epistemic humility, and more intentional teamwork.

LSP Models as a Boundary Objects

Within Iteration 5, the models produced during the Lego® Serious Play workshop also functioned as *boundary objects*—material-symbolic artefacts that enable shared reference without requiring disciplinary consensus.

Students' reflections indicate that the models supported the translation of complex environmental and social issues into tangible and discussable forms. Several teams reported that their project themes emerged directly from the LSP workshop. For instance, one team noted that *"this theme arose in the Lego Serious Play workshop" (I5 T1 Final Report)* , while another stated that *"after the Lego Serious Play, our group decided we wanted our piece to tackle the issue of fast fashion and consumerism" (I5 T4 Art Female)*. These accounts suggest that the models functioned as mediating structures through which abstract systemic concerns could be externalised and collectively negotiated.

The interpretive flexibility of the models was particularly evident in students' observations of divergent yet coexisting meanings. One student described it as *"fascinating"* that the same symbolic figure could be interpreted in *"20+ different ways, even with the lack of resources and the randomness of the Lego blocks" (I5 T2 Eng Male)*, while another highlighted the *"amount of different ideas that could formulate in a fairly short period of time, stemming from essentially the same prompt and materials but different people" (I5 T1 Art Female)*. These observations align closely with Star & Griesemer's (1989) assertion that boundary objects derive their power not from uniformity, but from their capacity to sustain productive multiplicity across social worlds.

Finally, students' reflections indicate that the playful and material nature of the models lowered communicative and affective barriers. One participant noted that LSP *"forces you to step out of your comfort zone and consider aspects of creation that you otherwise may not have stumbled upon"* (I5 T1 Art Female), illustrating how the activity supported exploratory dialogue without the pressure of early conceptual formalisation.

Within the TD-SDT framework, these findings position LSP models as effective boundary objects that facilitate communication across disciplinary boundaries by enabling shared sensemaking, legitimising multiple epistemic viewpoints, and supporting early-stage ambiguity tolerance.

Synthesis

Synthesising across tools, Iteration 5 demonstrates that transdisciplinary knowledge creation was mediated less by disciplinary integration alone than by *relational, reflexive, and material infrastructures*. No single tool generated transdisciplinary collaboration independently; rather, collaboration emerged through their *sequenced and complementary deployment*.

The *Teach-a-Skill activity*, situated within a community of practice, established trust and reciprocity among team members. *Open challenges* sustained productive ambiguity, encouraging exploration before premature convergence. *Formal analysis* sharpened perceptual awareness and shared observation. *Lego® Serious Play* enabled abstract exploration and boundary negotiation through symbolic modelling. *ITP Metrics* surfaced relational dynamics and prompted reflexive dialogue about collaboration practices.

Together, these tools scaffolded a progression from *social alignment*, through *epistemic disruption*, toward *integrative sense-making*. In this sense, the arts-based and design-oriented tools introduced in this iteration functioned not as supplementary enhancements but as *epistemic and ontological enablers* of transdisciplinary work, shaping how participants related to one another, to uncertainty, and to the knowledge they co-produced.

However, analysis of the assessed TD Process dimensions reveals an important limitation. Iteration 5 demonstrated that *strong collaborative process quality does not automatically produce deep epistemic integration*. Teams exhibited high levels of trust (C1), mutual learning (C3), and equal footing (C6), indicating that relational and communicative conditions were effectively established. Reflexivity tools such as ITP Metrics and formal analysis also helped surface disciplinary positioning and redistribute epistemic authority.

Despite these strong collaborative indicators, *integration depth (K2) and novelty (K3) remained moderate*. The resulting artefacts demonstrated coherent multidisciplinary coordination, yet conceptual restructuring across disciplinary frames was limited. Teams worked effectively together, but the resulting synthesis often remained additive rather than transformative.

Iteration 5 therefore revealed a critical distinction between *collaborative process quality and epistemic integration depth*. While coordination and mutual learning enabled productive interaction, they did not, on their own, produce transdisciplinary synthesis. These findings suggest that although relational infrastructure is necessary for epistemic crossing, it is insufficient to guarantee deep integration.

5.3.4.2 TD-SDT Evolution

Iteration 5 marked a structural consolidation phase in the evolution of the TD-SDT. Artistic methods were no longer treated as supplementary enhancements but became embedded within the collaborative process as epistemic infrastructure. Ambiguity was intentionally sustained through open challenges, while reflexive and relational tools, such as ITP Metrics and Teach-a-Skill, helped stabilise team dynamics. Formal analysis and Lego® Serious Play introduced structured practices of perceiving, abstracting, and playing, extending design thinking into aesthetic and symbolic domains.

This iteration also clarified a key distinction within the TD-SDT architecture: strong collaborative process quality (C-dimensions) did not automatically result in deep epistemic integration (K-dimensions). Teams demonstrated high trust, mutual learning, and equal footing, yet integration depth and novelty remained moderate. Iteration 5 therefore showed that relational infrastructure is necessary but insufficient for transformative synthesis. Additional scaffolding was needed to support deeper epistemic reframing across disciplinary perspectives.

Table 39, *Iteration 5 Evolving TD-SDT*, summarises the framework configuration at this stage of development.

Table 39 Evolution of the TD-SDT - After Iteration 5

TD-SDT Dimensions	Concept	Representative Tools / Practice	Iteration Introduced
Ambiguity	Tolerance for uncertainty	Open challenge: with few constraints (helps creativity)	3
Trust	Psychological safety for collaboration	Safe-space creation - create & protect safe-space for vulnerability	3
		Informal team building (shared meals, games)	3
		Team-level decision making	3
Epistemic Reflexivity	Awareness of disciplinary assumptions	Discipline appropriate recruiting / scaffolding	1
		ITP Metrics – Personality Types	2,5
		Recognition of epistemic differences (artists focus on *Why*, engineers focus on *How*)	3

		Reflexive prompt, reflexive journaling	5-7
		Multiple Intelligences	5
Epistemic Humility	Equal participation across disciplines	Equal Footing in collaboration	3-4
		Stereotype deconstruction	4
Epistemic Friction	Productive negotiation of difference	Productive friction, and slowing decision process	3,4
Mutual Learning	Community-based knowledge exchange	Community of Practice	3
		Process-driven approach	3
		Student-centred approach	3
		Team Contract	2-3
		Teach-a-skill	5
Epistemic Boundary Mediation	Boundary Object	Prototypes, shared lexicon, collaborative artifact	3-5
	Symbolic Infrastructure	Art installation	3-5
Enabling Infrastructu re	Project organisation	Design Thinking / Double-Diamond	2-3
		Client / art-client-model	2-3
		Iterative Prototyping	2-3
Art-Studio Pedagogies	Artistic inquiry methods	Object-Based Enquiry	2-3
		Critique (feedback)	2-3
		Exhibit of Artifacts.	2-3
Artistic Exposure	Artistic reference and inspiration	Curated art presentation	2-3
		Artist Talk	3
Creativity	Perceiving	Formal Analysis	5
	Abstracting	Lego Serious Play	5
	Playing	Lego Serious Play	5
	Modelling	Prototyping	5

5.3.4.3 Contribution of Iteration 5 — *Epistemic Negotiation and Concept Development*

Iteration 5 highlighted how multidisciplinary teams engaged in epistemic negotiation as they reconciled differing disciplinary perspectives during concept development. The findings demonstrated that abstraction, reflection, and dialogue supported the emergence of shared conceptual frameworks across disciplines. These dynamics further clarified how TD-SDT tools facilitate integrative knowledge creation.

5.4 Iteration 6 - STEAM Design Course: Ambiguity and Artistic Data Visualisation (2022)

5.4.1 Plan - Iteration 6

5.4.1.1 STEAM Design Challenge and Research Focus

STEAM Design Challenge: In partnership with the City of Ottawa Open Data Department, students were asked to transform raw municipal datasets of their choosing into meaningful, sustainability-oriented artistic data visualisations. The challenge was framed through the 13 United Nations Sustainable Development Goals (UN SDGs) (United Nations, 2025), with the aim of uncovering hidden stories in the data and communicating them through compelling narratives and aesthetic forms.

TD-SDT Research Focus: Iteration 6 revisited the concept–tool pairing of *ambiguity / open design challenge* to push students beyond disciplinary comfort zones and introduced *storytelling* as a narrative tool for artistic data visualisation. The guiding questions were: *How do students navigate highly open-ended design challenges?* and *What kinds of constraints are required to balance creativity with feasibility and productivity?* Within this iteration, artistic data visualisation served as the medium through which storytelling, sustainability, and data interpretation were intentionally brought together.

5.4.1.2 Data Collection & Analysis Plan

Data sources included four reflective journals per student (Weeks 4, 6, 9, and 12), team artifacts (prototypes and final outputs), and one researcher observation journal. Reflective journals documented learning trajectories (questions in APPENDIX O). Text-based sources (journals and final reports) provided evidence of TD collaboration and learning outcomes, while artifacts supported assessment of TD knowledge creation.

Consistent with Section 5.2, text-based data were analysed using a hybrid inductive–deductive thematic analysis approach to extract evidence of student experience related to TD collaboration and knowledge creation. Final artifacts were assessed for TD knowledge creation through integration quality using TIQS (Section 5.2.3.2). Researcher observations were analysed using critical incident analysis to identify moments of breakdown, shift, or unexpected success that shaped interpretation and subsequent refinement of the toolkit. Results are presented in the Observe section below.

5.4.2 Act - Iteration 6

5.4.2.1 Implementation

This iteration centred on artistic data visualisation. Students were introduced to the UN SDGs, exemplary 2D and 3D data visualisations, and common visualisation tools such as Tableau. Curated examples illustrated how storytelling can transform data into communicative, affective, and aesthetically engaging forms. Students worked in four multidisciplinary teams (4–6 students), each selecting a dataset, linking it to one or more SDGs, and producing a final visualisation.

City of Ottawa representatives introduced the civic context of open data—accessibility, shareability, and public value—explaining that the city's 2010 declaration to make data "open" aimed to enhance citizens' quality of life. Students were challenged to uncover untold stories in the data and communicate them through artistic visual narratives using a medium of their choice. To support feasibility, training was provided in data exploration, cleaning, and manipulation. Each team produced a final visualisation and presented it to faculty, peers, and City representatives; students also documented their process through journals.

5.4.2.2 TD-SDT Components Studied

Iteration 6 deliberately amplified *ambiguity* through a highly open-ended challenge. Teams were given broad technical and artistic freedom to transform raw City of Ottawa data into sustainability-oriented visualisations linked to at least one SDG. In parallel, storytelling was introduced as a narrative strategy for translating complex datasets into accessible and meaningful forms of communication.

To support this shift, students engaged with curated examples of artistic data visualisation that combined narrative, aesthetics, and data, and explored tools such as MS Excel, Power BI, and Tableau. Teams were also encouraged to experiment with artistic approaches including drawing, whiteboard animation, and interactive programming libraries such as D3.js and p5.js. As discussed in Section 2.5.2.5, open challenges with minimal constraints increase ambiguity, a condition that can support creativity and problem reframing (Cross, 2006; Dorst, 2019; Kolko, 2010; Lawson, 2006; Rittel & Webber, 1973).

5.4.3 Observe - Iteration 6

5.4.3.1 Overview Data Collected

Iteration 6 involved four teams and 22 students (6 arts, 8 engineering, and 8 DTI; 12 females and 10 males; Table 40). Data included 76 individual reflective journal entries (four per student; prompts provided in APPENDIX O), which were collated into 21 student journals, as well as 4 final reports, 9 intermediary prototypes, 5 final artifacts, and 1 researcher observation journal. A summary of the final artifacts is presented below, while detailed documentation of prototype evolution and final outputs is provided in APPENDIX S. Representative excerpts from student reflections and researcher observations are discussed in the Reflect section (Section 5.4.4).

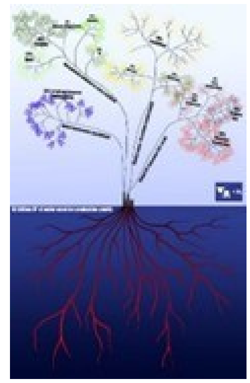
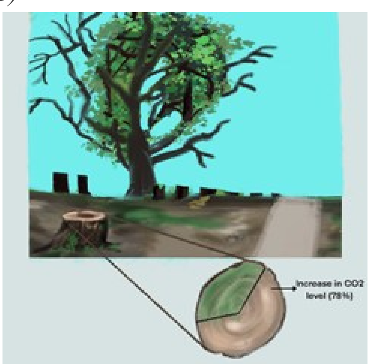
Table 40 Iteration 6 Data Collected

Iteration 6 - Data Collected														
Identification								Individual Data		Team Data			Researcher Data
Iteration	Teams	N Students	A	E	O	F	M	Journals	Collated Journals	Final Reports	Prototypes	Final Artifacts	Journal
6	1	6	2	3	1	3	3	19	6	1	3	1	
	2	4	1	0	3	3	1	15	4	1	2	1	
	3	6	2	2	2	3	3	19	6	1	2	1	
	4	6	1	3	2	3	3	23	5	1	2	2	
6	4	22	6	8	8	12	10	76	21	4	9	5	1

5.4.3.2 Artifacts Produced

Across Iteration 6, four teams produced data-informed artistic prototypes addressing sustainability and social challenges (Table 41). Among the four teams, five final artifacts were produced, as Team 4 developed two related outputs within the same project. Two teams focused on fast fashion and waste (SDG 12). Team 1 created a narrative-driven whiteboard animation highlighting the cumulative environmental impacts of overconsumption. Team 2 used a visually compelling tree metaphor to expose the “dark side” of fast fashion by contrasting aesthetic appeal with ecological degradation. Team 3 addressed deforestation in India (SDG 13) through an illustrated storybook translating scientific data into narrative and illustration. Team 4 addressed violence against women during COVID-19 (SDG 3) through an interactive global data visualisation paired with a narrative comic. Together, these artifacts illustrate how artistic visualisation can mediate complex data and narratives to foster awareness and reflection.

Table 41 Iteration 6 Final Artifacts

Team 1 – Fast Fashion and Waste (SDG-12) 	*Team 2 – Dark Side of Fast Fashion (SDG 12)* 
Team 3 – Amit's Storybook about India`s Forests (SDG 13) 	
Team 4 – The Shadow Pandemic (SDG 3) 	*Team 4 – The Shadow Pandemic (SDG 3)* 

Detailed prototype evolution and final artifact documentation are provided in APPENDIX S.

5.4.3.3 Observational Findings

The 21 collated journals and four final reports were analysed to identify evidence of how Iteration 6 tools shaped TD collaboration and TD knowledge creation.

Inductive Thematic Analysis – General Topics Discussed

Inductive thematic analysis revealed three recurring themes: students initially experienced multidisciplinary collaboration as intimidating, design was understood as iterative rather than linear, and storytelling emerged as a powerful tool for humanising data.

Several students described intimidation early on. A Team 1 male engineering student noted, *"This class is obviously made up of many students from different degrees and of different ages, which at first kind of scared me as a first-year student"* (I6 T1 S3 Eng Male). A Team 2 female art student similarly wrote, *"I heard the words 'master's degree', 'experience in the field' and 'STEM' repeatedly... I felt out of place and slightly intimidated"* (I6 T2 S1 Art Female). Over time, disciplinary diversity became a resource for broader exploration—though students also recognised the coordination demands of working across different work styles. A Team 1 female engineering student observed, *"Having people from such diverse backgrounds can make it really challenging to have homogeneous decisions or consensus,"* adding that engineers tend to be *"methodical, calculated and convergent thinkers"* while arts students are *"liberal and divergent thinkers"* (I6 T1 S4 Eng Female). By the end, students framed creativity as shared across backgrounds: *"regardless of background and profession, everyone possesses a certain level of creativity that they express in different ways"* (I6 T4 S4 DTI Male).

Students also emphasised that the design process was iterative rather than linear: *"I experienced first-hand that design is an iterative process, not a linear one"* (I6 T1 S6 DTI Female). Teams used creativity tools to coordinate ideas—for instance, *"Mind mapping was helpful to our project as it put all our ideas in one MIRO document for us all to see clearly"* (I6 T1 Final Report). Abstraction supported reframing: *"Abstraction allowed us to take a step back and go back to the essence of the problem we were trying to solve"* (I6 T4 Final Report). In several cases, iteration involved significant pivots when early concepts were judged unfeasible for the story being told.

Finally, students repeatedly emphasised storytelling to humanise data and activate affect. One student noted, *"For the very first time, looking at data activated me to an emotional level rather than just cognitive one"* (I6 T3 S2 DTI Male). Another highlighted how visualisation could be artistic and message-driven: *"the first key takeaway is that designing a data visualisation can be fun and artistic... we had learned to send our key message in a stunning illustration"* (I6 T2 S3 DTI Female). Teams aimed to *"intentionally merge our hard data with human experiences; crafting an engaging narrative that is anchored by facts"* (I6 T4 Final Report).

Across these accounts, success was framed not only as a final artifact but also as personal growth and willingness to stretch into new competencies. One student reflected, *"volunteered to assist with the information/education aspect of the project in order to overcome my aversion to research and data analysis"* (I6 T1 S6 DTI Female). The projects were widely framed as aiming beyond the classroom—encouraging viewers to reevaluate habits and engage sustainability issues more critically.

Researcher's Key Observational Notes

The researcher journal identified *critical incidents* that shaped Iteration 6. The challenge was experienced as highly open and cognitively demanding, particularly because many students had limited prior exposure to open data, data cleaning, and interpretation. Several students described struggling to understand what the course expected them to produce. One participant explained that the concepts initially felt "so vague and foreign" (I6 T1 Eng Male), while another reported that it was "very difficult to understand what was being asked of us" (I6 T4 Art Female). In some cases this uncertainty produced frustration and loss of confidence; a student reflected that after realising their misunderstanding of the assignment they felt "very defeated," and during concept development were "completely frozen" (I6 T4 Art Female). These accounts suggest that the high level of ambiguity, combined with unfamiliar technical requirements, sometimes exceeded students' capacity to navigate the task productively.

Deductive Thematic Analysis for each TD-SDT Tool of this Iteration

This section applies the same deductive thematic analysis workflow described in Section 5.2 (and used in Iteration 5) to examine the performance level of each dimension of the TD-Process Assessment Framework in Iteration 6.

The results of this deductive analysis are presented below. As Iteration 5 provided a comprehensive account of the operationalisation of the TD Process Assessment framework, the analyses of Iterations 6 and 7 emphasise outcomes and interpretive findings rather than methodological process.

5.4.3.4 TD Process Assessment (TDP)

Using the TD Process Assessment methodology defined in Section 5.2, 160 student quotes were extracted, and team-level scores were derived for each dimension and synthesised into a *TD Process Score* per team (Table 42). In Iteration 6, Team 1 achieved a high score (6.10), Teams 2 and 4 fell in the medium range (4.83 and 3.38), and Team 3 was low (2.32). The iteration average was 4.16 (medium).

Table 42 Iteration 6 TD Process Assessment

I6 TD Process Assessment Framework					I6 TD Process Assessment			
				I6	T1	T2	T3	T4
TD Process Quality – TD Collaboration			**TPQ Score**	**1.71**	**2.71**	**2.00**	**1.43**	**0.71**
	Collaborative Process	C1- Trust	L/M/H [0,3]	2.00	2.00	3.00	2.00	1.00
		C2- Communication		2.25	3.00	3.00	1.00	2.00
		C3- Mutual Learning		2.25	3.00	3.00	3.00	0.00
		C4- Conflict Handling (Friction)		1.25	2.00	0.00	2.00	1.00
		C5- Shared Problem Framing		1.50	3.00	3.00	0.00	0.00
	Reflexivity	C6- Equal Footing, Power Relationships & Fairness		0.75	3.00	0.00	0.00	0.00
		C7- Team Critical Self-Awareness		2.00	3.00	2.00	2.00	1.00
TD Integration Quality – TD Knowledge Creation (Tangible)			**TIQ Score**	**1.19**	**1.39**	**0.83**	**0.89**	**1.67**
	Artifacts Created	K1- Epistemic (Disciplinary) Grounding	L/M/H [0,3]	1.71	1.67	1.50	0.67	3.00
		K2- Integration Depth & Coherence		0.63	1.50	0.00	1.00	0.00
		K3- Advancement of Understanding (Novelty)		1.25	1.00	1.00	1.00	2.00
TD Societal Effects – TD Knowledge Creation (Intangible)			**TSE Score**	**1.25**	**2.00**	**2.00**	**0.00**	**1.00**
	Learning & Capacity Building of Participants	K4- Cognitive, Social & Practical Competencies	L/M/H [0,3]	1.25	2.00	2.00	0.00	1.00
	Societal Usefulness	K5- Salient, Credible, Legitimate, Actionable						
	Societal Impacts	K6- Policy & Practices Change						
TD Process Score [0,9] where: Low =[0,2]; Medium=[3,5]; High=[6,9]			**TD Process Score**	**4.16**	**6.10**	**4.83**	**2.32**	**3.38**
			L/M/H [0,9]	**M**	**H**	**M**	**L**	**M**

Figure 15 visualises TD Process Score for each team as the sum of TPQ, TIQ, and TSE score (0–3 each). The stacked bar chart visually represents their relative contributions to the overall TD Process Score, where team 1 obtained the highest scores of 6.10 .

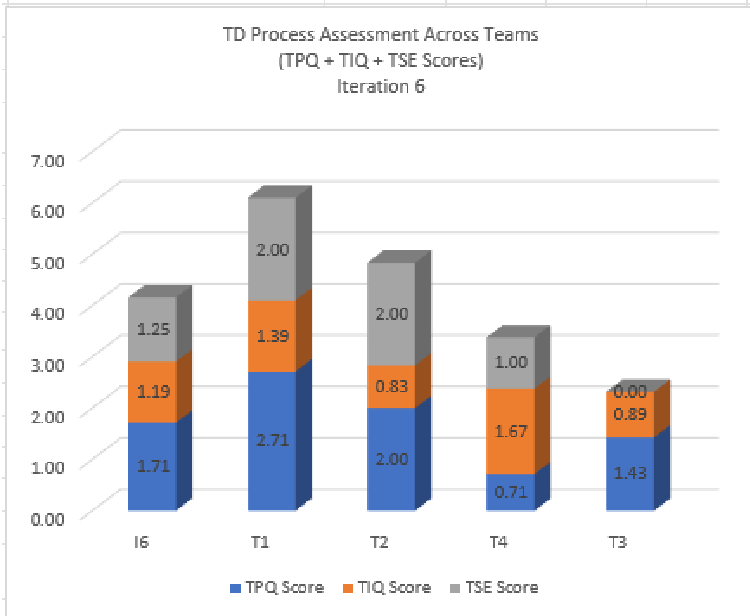


Figure 15 Iteration 6 TD Process Score - TPQ+TIQ+TSE Scores

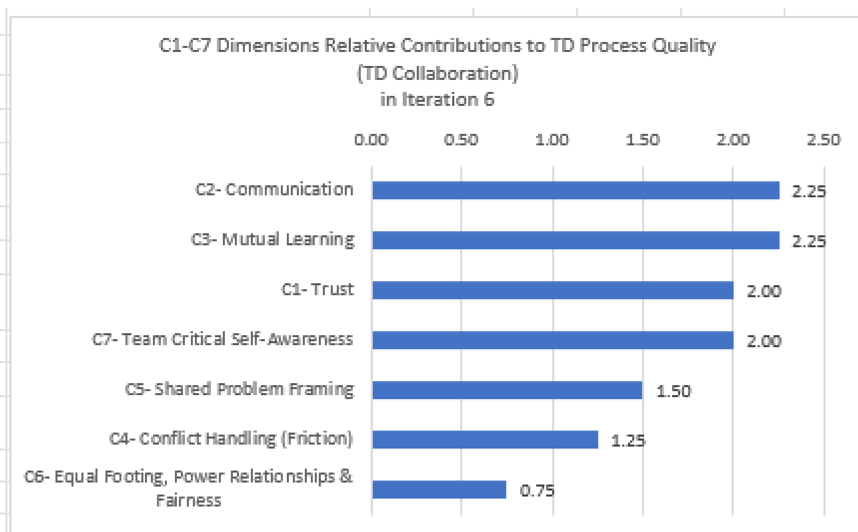


Figure 16 Iteration 6 Relative Importance of Each TD Process Dimension Assessed

Figure 16 presents the relative contributions of the C1–C7 dimensions to the overall TD Process Quality (TD Collaboration) score in Iteration 6. Each iteration-level score represents the average of team-level scores and ranges from 0 to 3.

In iteration 6, a high contribution (2.25) was observed for C2-Communication and C3-Mutual Learning. Medium contributions (2.00) were observed for C1-Trust and C7-Team Critical Self-Awareness and (1.50 & 1.25) for C5- Shared problem framing (2.20), and C4-Conflict handling

(1.25). And Low contribution was observed for C6-Equal Footing, Power Relationship & Fairness was (0.75).

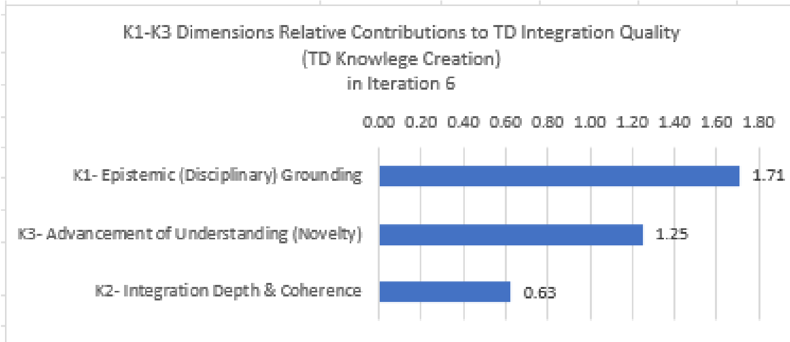


Figure 17 Iteration 6 K1-K3 Relative Contributions to TD Integration Quality (TIQ)

Figure 17 presents the relative contributions of K1–K3 to the overall TD Integration Quality (tangible TD Knowledge Creation) score. As with TPQ, iteration-level scores represent averages of team-level scores and range from 0 to 3.

In Iteration 6: K1-Epistemic Grounding (1.71), K3-Novelty/Advancement of Understanding) (1.25), and K2- Integration Depth and Coherence (0.63).

All three dimensions fell within the lower-to-moderate range, indicating emerging but not yet deep integration across teams.

As Iteration 5 provided a comprehensive account of the operationalisation of the TD Process Assessment framework, only the results of Iteration 6 assessment are represented in Table 42.

5.4.3.5 TD-SDT Tool Contribution Assessment

The assessment of TD-SDT concept–tool contributions to TD collaboration and TD knowledge creation draws on the TD Process Assessment dimensions theoretically expected to be activated as explained in Sections 2.6 and 5.2.4.

Deductive Thematic Analysis for each TD-SDT Tool of this iteration

This section applies the same deductive thematic analysis workflow described in Section 5.2 (and used in Iteration 5) to identify evidence of how Iteration 6 TD-SDT concept/tool pairs manifested across the TD Process dimensions. Table 43 presents the resulting distribution of tool-relevant excerpts across teams and the iteration.

Table 43 Iteration 6 Deductive Analysis of TD-SDT Concept/Tool Pairs

TD-SDT Components Introduced in I6		Number of Quotes per Team				Total
Concept	**Tool**	**T1**	**T2**	**T3**	**T4**	**I7**
Ambiguity	Open Design Challenge	11	6	8	10	35
Storytelling	Data Visualization	14	10	9	8	41
Total Number of Quotes		25	16	17	18	76

A complete list of extracted quotes is available in the data repository. Key excerpts used as evidence are presented in the Reflect section (Section 5.4.4).

Assessment of TD-SDT Concept/Tool Pairs

Having established TD Process Assessment profiles for the iteration, this section examines the *contribution of each TD-SDT concept/tool pairs* to the TD collaboration and knowledge creation outcomes in Iteration 6.

Concept/tool pairs implemented in this iteration, along with their mapped TD Process dimensions, are listed in Table 44 (complete mapping presented in APPENDIX L). Concept/Tool contributions were assessed using the *TD Process Contribution Assessment* described in Section 5.2.4, which aggregates relevant TD Process Assessment scores for the dimensions activated by each concept/tool pair.

Table 44 Iteration 6 Concept/Tool Pairs Mapping

TD-SDT Components Introduced in I6		TD Process Framework Mapping	
Concept	**Tool**	**TD Collaboration**	**TD Knowledge Creation**
Ambiguity	Open Design Challenge	C5, C4, C7	K3 (strong), K2, K4
Storytelling	Data Visualization	C2, C5	K5 (strong), K2, K1, K3

Table 45 presents the resulting concept/tool contribution profiles. The Iteration 6 values of each TD Process Assessment Dimensions (C1-C7 & K1-K6) appear in the first column. The next 3 columns present the assessed efficiency of each tool in contributing to the overall TD Process for iteration 6. Ambiguity – Open Challenge, and Storytelling – Data Visualisations were assessed as having medium impact on the TD Process.

Table 45 Iteration 6 TD SDT Tool Assessment

I6 TD Process Assessment Framework				I6	I6 - Tool Assessment	
				Average	Ambiguity - OC	Storytelling Data Viz
TD Process Quality – TD Collaboration			**TPQ Score**	**1.71**	**1.58**	**1.88**
	Collaborative Process	C1- Trust	L/M/H [0,3]	2.00		
		C2- Communication		2.25		2.25
		C3- Mutual Learning		2.25		
		C4- Conflict Handling (Friction)		1.25	1.25	
		C5- Shared Problem Framing		1.50	1.50	1.50
	Reflexivity	C6- Equal Footing, Power Relationships & Fairnes		0.75		
		C7- Team Critical Self-Awareness		2.00	2.00	
TD Integration Quality – TD Knowledge Creation (Tangible)			**TIQ Score**	**1.19**	**1.62**	**1.62**
	Artifacts Created	K1- Epistemic (Disciplinary) Grounding	L/M/H [0,3]	1.71		
		K2- Integration Depth & Coherence		0.63	0.63	0.00
		K3- Advancement of Understanding (Novelty)		1.25	1.25	
TD Societal Effects – TD Knowledge Creation (Intangible)			**TSE Score**	**1.25**	**1.25**	**0.00**
	Learning & Capacity Building of Participants	K4- Cognitive, Social & Practical Competencies	L/M/H [0,3]	1.25	1.25	
	Societal Usefulness	K5- Salient, Credible, Legitimate, Actionable		0.00		0.00
	Societal Impacts	K6- Policy & Practices Change		0.00		
TD Process Score [0,9] where: Low =[0,2]; Medium=[3,5]; High=[6,9]			**TD Process Score**	**4.16**	**4.45**	**3.49**
			L/M/H [0,9]	**M**	**M**	**M**

Figure 18 shows graphically how each specific concept/tools contributed to TD Process dimensions in this iteration.

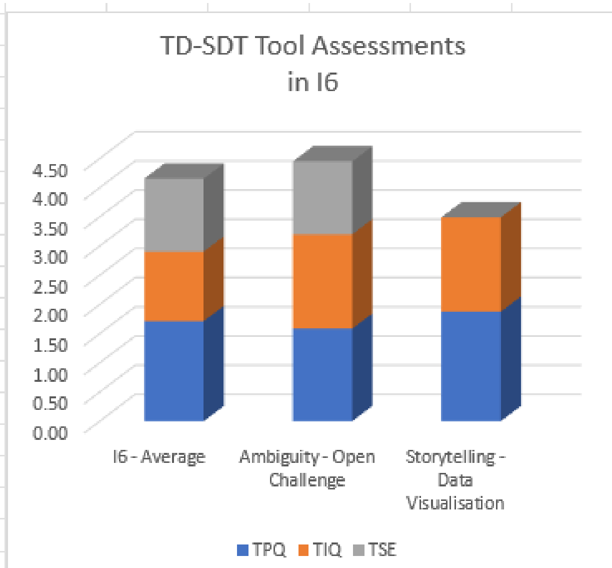


Figure 18 Iteration 6 Tool Assessment

So, Ambiguity – Open Challenge, and Storytelling – Data Visualisation have a moderate influence on the TD Process score in Iteration 6.

5.4.3.6 Observe Synthesis

Iteration 6 introduced heightened ambiguity and expanded narrative and aesthetic exploration through artistic data visualisation and open-ended framing. These conditions generated increased conceptual experimentation and, in some teams, stronger novelty (K3). However, integration depth (K2) remained uneven across teams.

The iteration revealed that ambiguity and friction alone do not reliably produce coherent synthesis. In several cases, high epistemic openness led to confusion, repeated reframing, and stalled progress. Where stabilising mechanisms were insufficient, teams struggled to consolidate integrative insights.

5.4.4 Reflect - Iteration 6

5.4.4.1 Key Insights

Iteration 6 showed that *ambiguity is a threshold condition*: when it is not scaffolded, it can shift from a driver of creativity to a barrier to collaboration and learning. Although the iteration produced several innovative artistic data-visualisation outcomes, these successes often emerged only after *intensive faculty intervention*. Many students entered with limited experience in data cleaning, analysis, and visualisation. Combined with broad freedom over datasets, tools, and storytelling formats, this produced confusion, repeated restarts, and stalled progress. One student reflected that the project requirements initially felt *"so vague and foreign, making it difficult to identify an appropriate direction" (I6 T1 Eng Male),* while another noted that *"having never worked on a project like this one, it was very difficult to understand what was being asked of us" (I6 T4 Art Female).* In several teams, frustration and task conflict increased, especially where workload and coordination were amplified by larger group sizes. At the same time, the struggle also produced deep learning: students became more aware of how data is interpreted, where disciplinary blind spots surfaced, and how collaboration changes under pressure.

Ambiguity - Open Design Challenge

In this iteration, *high and unbounded ambiguity* hindered creativity and collaboration more often than it supported them.

Students frequently described the open challenge as overwhelming, particularly in the early stages of the project. One participant explained that *"initially we struggled to understand what exactly is required for a successful final project," which delayed the emergence of viable ideas (I6 T1 Eng Male*). Another reflected that the experience produced moments of frustration and paralysis: *"So, when it came to the development of concepts, I was completely frozen… it was more than defeat; it was frustration and at times confusion too" (I6 T4 Art Female)*. These accounts suggest that ambiguity exceeded productive levels for several teams, preventing exploratory creativity from emerging until additional guidance and iteration occurred.

The open challenge offered minimal constraints across data selection, tools, and narrative strategy—an approach that proved overwhelming for students unfamiliar with working with large datasets. Instead of enabling exploratory sense-making, many teams experienced paralysis and repeated restarts. This aligns with design and organisational research emphasising that psychological safety and bounded uncertainty are prerequisites for productive exploration (Dorst, 2019; Edmondson, 2012). Students captured both the emotional toll and eventual growth that followed: *"It was more than defeat; it was frustration and at times confusion too. But with patience and perseverance, I reached this learning potential in the class." (I6 T4 Art Female).* Even in stronger teams, the cost of repeated resets raised questions about feasibility: *"Having to restart our project three times puts into question just how much success our team was realistically experiencing." (I6 T4 Eng Female)*

At the same time, students also recognised the upside of freedom when conditions supported productive exploration: *"By giving us the power to take on the design however we choose, [it] opened the door to some of the best brainstorming sessions I have ever experienced." (I6 T4 Eng Female)*

These accounts refine the TD-SDT Ambiguity / Open Design Challenge component: ambiguity needs to be *designed, tuned, and staged over time*. In Iteration 6, excessive openness often suppressed collaboration rather than strengthening it, confirming that ambiguity alone does not guarantee TD knowledge creation.

Storytelling - Artistic Data Visualisation

Storytelling emerged as a powerful tool for meaning making, but it was also cognitively demanding and often required guidance to move from aesthetic exploration to communicative clarity. Students described learning how narrative supports audience connection and sense-making: *"I learned that the best way to connect to an audience is by telling a story and that not all stories are conducive to teaching a lesson."* (I6 T4 Eng Male). They also described how critique and feedback were essential for shaping coherence: *"With the feedback we received from our peers and the professors, we were able to create a storyline that fitted our subject."* (I6 T1 Art Female).

From a TD-SDT perspective, storytelling functioned as a TD Communication tool, translating data across epistemic domains. However, it only operated effectively when embedded within critique, feedback, and narrative scaffolds—confirming storytelling as a mediated boundary-crossing practice, not an intuitive or standalone skill.

Data Visualisation Tools - Data Literacy

Limited data literacy strongly constrained what teams could do with disciplinary diversity. Many students entered without experience in data cleaning, analysis, or visualisation, which compounded the effects of the open challenge and contributed to underdeveloped early prototypes and repeated restarts. Over time, students described a deepened understanding of the field itself: *"I learned that data visualisation is much deeper than I once thought."* (I6 T4 Eng Male). Several also developed a more critical view of data: *"I learned that data is biased and not as straightforward as I thought it was."* (I6 T4 Eng Male).

Within the TD-SDT, this highlights technical scaffolding as a form of enabling infrastructure: without it, reciprocal exchange was delayed and disciplinary diversity was neutralised. Yet these gaps also became sites of epistemic learning, pushing students to recognise the constructed nature of "data-driven" knowledge.

Disciplinary Diversity - Multidisciplinary Collaboration

Iteration 6 also demonstrated that disciplinary diversity alone was not sufficient to generate integrative collaboration under high ambiguity and time pressure. In several teams, disciplinary roles became instrumental rather than exchanged, with participants retreating into familiar identities to ensure progress: *"It led me to capitalise on [being an engineer] and not take any risks"* (I6 T4 Eng Male). Conversely, when conditions allowed time for dialogue, students described diversity as a benefit: *“It was easier than working with only engineers because of their new views and angles”* (I6 T4 Eng Male).

This insight reinforces the TD-SDT Community of Practice logic: diversity becomes an asset only when supported by shared skill-building, time for dialogue, and reduced epistemic risk. Without these conditions, collaboration tends to collapse into parallel work rather than mutual learning.

Reflexivity - Faculty Scaffolding

Faculty facilitation functioned as essential enabling infrastructure in Iteration 6—supporting boundary negotiation, helping teams narrow their scope of work, and sustaining motivation long enough for projects to converge. Students named this support directly: *“The professors of this class were always present… which really helped in keeping that motivation going”* (I6 T4 Eng Female). Importantly, journals also show that struggle itself became a catalyst for reflexivity: under pressure, students became more aware of assumptions, collaboration habits, and learning limits.

At the same time, several students later described how these struggles prompted deeper reflection on their learning and collaboration practices. One participant observed that the difficulty of the project *“made us work harder and explore so many different avenues,” encouraging broader exploration of possible approaches (I6 T4 DTI Male)*. Another reflected that repeated restarts ultimately deepened their understanding of the field: *“When my team and I had to redo our work several times… it solidified all the knowledge I now have” (I6 T4 Art Female).* These reflections suggest that while ambiguity initially destabilised teams, it also created conditions for reflexive learning when supported by sustained facilitation.

In TD-SDT terms, reflexivity did not arise despite difficulty, but through difficulty—when supported by facilitation and trust.

Project Trajectories: Struggle and Resolution in Teams 2 and 3

Across Iteration 6, teams initially struggled with the open-ended nature of the artistic data visualisation challenge. Many students had limited experience working with open datasets, and the combination of data interpretation, storytelling, and artistic representation created early uncertainty. Progress typically emerged only after several iterations of ideas, prototypes, and feedback.

Team 2 initially had difficulty identifying how to translate sustainability data into a coherent artistic narrative. Through repeated discussions, prototype iterations, and feedback from peers and instructors, the team gradually converged on a concept addressing the environmental impact of fast fashion. Reflections indicate that collaboration evolved toward equal footing, with disciplinary perspectives contributing in complementary ways. One member noted: that their ideas were treated as equally valid within the team, enabling contributions from both artistic and technical perspectives. This art student felt intimidated by the STEM backgrounds of her teammates and feared being useless, but found her contributions were highly valued: "Turns out I was not useless at all. My teammates listened to me and viewed my ideas as equal to theirs. All I had to do was to put myself out there." (I6 T2 Art Female) An engineering teammate similarly reflected: "I had learned a lot from Ana who is far more experienced in art concepts... Together we worked to be able to transform the data that I had collected into the illustration of a tree." (I6 T2 Eng Female) This environment of mutual respect, combined with iterative refinement and critique, helped the team transform early uncertainty into a visually compelling narrative representation of fast fashion's hidden ecological costs.

Team 3 faced different challenges, including initial uncertainty about how to work with the dataset and how individual team members could contribute. Through discussion and experimentation, the team reframed the project as a children's story about deforestation in India, translating complex environmental data into an accessible narrative format. The process involved several conceptual shifts, including abandoning earlier ideas that proved unworkable. Students reflected on the importance of revisiting and revising ideas: "The second lesson was that it is never too late to take a step back and rethink on the approach rather than wasting time on pushing something just because you want to stick with that idea." (I6 T3 DTI Male) Another noted: "My key takeaways from this course would be first to not get attached to our favorite ideas… The favorite idea is not necessarily the one that can be done in a manner fitting the schedule and team ability." (I6 T3 Eng Male) The team's willingness to pivot, combined with the variety of perspectives within the group, ultimately enabled the development of a coherent narrative artifact. Together, these project trajectories show that movement toward resolution occurred through cycles of iteration, feedback, and conceptual revision. Initial ambiguity and uncertainty were followed by successive refinements, shifts in direction, and the gradual emergence of coherent narrative forms. In both teams, collaboration, disciplinary diversity, and iterative development shaped the progression from early ambiguity toward final outcomes.

Synthesis

Iteration 6 foregrounded a key boundary condition within the TD-SDT: ambiguity must be calibrated and actively scaffolded to support transdisciplinary collaboration and knowledge creation. When insufficiently supported, ambiguity shifted from a creative catalyst to a barrier, amplifying data-literacy gaps, increasing restart cycles, and reducing the benefits of disciplinary diversity. At the same time, when supported by storytelling guidance, technical scaffolding, critique, and sustained facilitation, the same uncertainty produced meaningful learning and reflexive insight.

Students' reflections illustrate this dual dynamic. One participant noted that the difficulty of the project *"made us work harder and explore so many different avenues,"* while another reflected that repeated revisions ultimately *"solidified all the knowledge I now have"* (I6 T4 DTI Male; I6 T4 Art Female). These accounts show how ambiguity, when combined with sustained effort and feedback, can transform frustration into reflective learning.

More broadly, Iteration 6 demonstrates that productive transdisciplinary processes depend not on openness alone, but on how ambiguity, scaffolding, communication practices, and reflexivity are orchestrated together. The open-ended framing of the challenge enabled expanded narrative and aesthetic exploration through artistic data visualisation, which in some teams generated increased conceptual experimentation and moderate novelty (K3). However, integration depth (K2) remained uneven across teams.

These results indicate that ambiguity and epistemic friction alone do not reliably produce coherent synthesis. In several cases, high epistemic openness led to confusion, repeated reframing, and stalled progress. Where stabilising mechanisms—such as technical guidance, narrative scaffolds, or facilitative critique—were insufficient, teams struggled to consolidate integrative insights.

These findings suggest that generative tension must be balanced by stabilising structures. While friction and openness can stimulate conceptual expansion, they require complementary forms of coordination and scaffolding to sustain collaborative coherence. Iteration 6 therefore refines the TD-SDT by showing that epistemic transformation emerges from the dynamic interplay between destabilising forces (ambiguity, friction, exploration) and stabilising forces (scaffolding, facilitation, and shared artifacts).

5.4.4.2 TD-SDT Evolution

Iteration 6 refined the TD-SDT by revealing an important boundary condition for the design of transdisciplinary challenges. The project brief proved too open-ended relative to the technical and conceptual expertise that could be developed within a single academic term. The absence of clear constraints increased ambiguity beyond productive levels and frequently hindered progress. Larger team sizes also amplified coordination difficulties, with four-member teams appearing more manageable for data-intensive work.

The anticipated benefits of multidisciplinary collaboration were therefore harder to realise. Because many participants were simultaneously learning unfamiliar tools, data practices, and narrative techniques, opportunities for reciprocal knowledge exchange were reduced.

From a TD-SDT perspective, this iteration suggests that open challenges must be carefully bounded when they involve unfamiliar technical domains. Clearer constraints—such as limiting dataset scope, narrowing tool options, or specifying expected output formats—together with earlier and progressive scaffolding would likely support more effective collaboration and integration.

Table 46 Evolution of the TD-SDT - After Iteration 6

TD-SDT Dimensions	Concept	Representative Tools / Practice	Iteration Introduced
Ambiguity	Tolerance for uncertainty	Open challenge: with few constraints (helps creativity)	3-6
Trust	Psychological safety for collaboration	Safe-space creation - create & protect safe-space for vulnerability	3-6
		Informal team building (shared meals, games)	3,4
		Team-level decision making	3,4
Epistemic Reflexivity	Awareness of disciplinary assumptions	Discipline appropriate recruiting / scaffolding	1-6
		ITP Metrics – Personality Types	2,5
		Recognition of epistemic differences (artists focus on *Why*, engineers focus on *How*)	3
		Reflexive prompts, reflexive journaling	5,6
		Multiple Intelligences	5
Epistemic Humility	Equal participation across disciplines	Equal Footing in collaboration	3-4

		Stereotype deconstruction	4
Epistemic Friction	Productive negotiation of difference	Productive friction, and slowing decision process	3,4
Mutual Learning	Community-based knowledge exchange	Community of Practice	3-5
		Process-driven approach	3,4
		Student-centred approach	3,4
		Team Contract	2-4
		Teach-a-skill	5
Epistemic Boundary Mediation	Boundary Object	Prototypes, shared lexicon, collaborative artifact	3-5
	Symbolic Infrastructure	Art installation	3-5
Enabling Infrastructu re	Project organisation	Design Thinking / Double-Diamond	2-6
		Client / art-client-model	2-5
		Iterative Prototyping	2-6
Art-Studio Pedagogies	Artistic inquiry methods	Object-Based Enquiry	2-6
		Critique (feedback)	2-6
		Exhibit of Artifacts.	2-6
Artistic Exposure	Artistic reference and inspiration	Curated art presentation	2-5
		Artist Talk	3,4
		Storytelling, Artistic Data Visualisation, Visual Narrative	6
Creativity	Perceiving	Formal Analysis	5
	Abstracting	Lego Serious Play	5
	Playing	Lego Serious Play	5
	Modelling	Prototyping	5

5.4.4.3 Contribution of Iteration 6 — Deepening Integration Through Iterative Design

Iteration 6 demonstrated how iterative design processes, combined with structured critique and reflective dialogue, supported deeper conceptual and disciplinary integration. Teams increasingly used artifacts and prototypes as boundary objects that mediated collaboration and knowledge exchange. This iteration reinforced the role of iterative making as a central mechanism within the TD-SDT.

5.5 Iteration 7 — STEAM Design Course – Future Imaginaries (2023)

This final iteration examined whether storytelling and philosophical reflection could strengthen TD collaboration and TD knowledge creation within the TD-SDT.

5.5.1 Plan – Iteration 7

5.5.1.1 STEAM Design Challenge and Research Focus

STEAM Design Challenge: Students reinterpreted historical artifacts from Ingenium—Canada's Science and Technology Museum—by narrating speculative past, present, and future scenarios. They then redesigned each artifact for a sustainable Anthropocene future and presented outcomes in a public exhibit (Design Day).

TD-SDT Research Focus: This iteration tested the integration of storytelling, philosophical reflection on time and space, creative thinking tools (perceiving—formal analysis, techno senses), embodied thinking, modelling/prototyping, storytelling)(Henriksen & Group, 2018; Root-Bernstein, 2015) and generative artificial intelligence (AI) as a co-creative partner (Boden, 2004; Shneiderman, 2022). The guiding research questions asked: whether storytelling and philosophy enriched TD collaboration and knowledge creation; how time/space-constructs oriented sustainability practices; and what role AI played in supporting creativity and reflection. The previously non-evaluated peer critique tool was also revisited.

5.5.1.2 Data Collection & Analysis Plan

Data sources collected included reflective journals (three submissions), prototypes, peer critique artifacts, course assignments, and teaching-team observation notes. Journals were submitted as assignments in Weeks 4, 6, and 12; prompts are provided in APPENDIX O. Design artifacts (three prototypes per team) and final installations were collected to support analysis of TD knowledge creation and learning trajectories. Researcher's observation notes were collected to document process evolution and critical incidents.

Consistent with Section 5.2, text-based data were analysed using hybrid inductive–deductive thematic analysis to extract evidence of student experience related to TD collaboration and knowledge creation. Final artifacts were assessed for TD knowledge creation through integration quality using TIQS (see Section 5.2.3.2). Researcher observations were analysed using critical incident analysis to identify moments of breakdown, shift, or unexpected success that shaped interpretation and subsequent toolkit refinement. Results are presented in the Observe section below.

5.5.2 Act - Iteration 7

5.5.2.1 Implementation

In Iteration 7, students engaged with chosen artifacts from Ingenium's science and technology collection. The course unfolded in three "acts": (1) encountering the artifact in its current form, (2) reconstructing an imagined past, and (3) projecting the artifact into a speculative future through sustainability-focused redesign.

The course enrolled 27 students (6 AHL, 9 GNG, 8 DTI) organised into six teams of 4–5 students. The structure emphasised shared learning across teams (CoP) through iterative storytelling, prototyping, and critique, culminating in a public Design Day exhibit. Each team produced two prototypes and one final artifact exhibited publicly.

5.5.2.2 TD-SDT Components Studied

Iteration 7 operationalised the TD-SDT through a structured three-act progression—Present, Past, and Future—sequencing specific tools (storytelling, philosophical prompts, creative thinking tools, and generative AI) to scaffold transdisciplinary engagement. Learning was organised within a community-of-practice (CoP) model, supported by iterative prototyping cycles, non-graded peer critique sessions, and a culminating public Design Day exhibition. Each team produced two prototypes and one final artifact.

Act 1 – The Present focused on direct engagement with an Ingenium artifact. Students individually conducted in situ multisensory formal analyses (materiality, scale, texture, sound; Section 3.9.2.1) of a chosen artifact using sketches, photography, and written analysis. After exploring technologically extended perception with CAD, VR, LiDAR, and NeRF tools, students created a 3D scan of their chosen artifact (using Scaniverse), generating an artifact digital representation. Students then wrote a short narrative from their artifact's perspective (embodied thinking) using structured storytelling frameworks (protagonist, antagonist, needs and wants, conflict, narrative structures; Pixar-in-a-Box, Disney Imagineering). Insights were then synthesised into a bilingual Timeline Card integrating image, 3D scan link, QR-linked AR content, and concise historical description.

Act 2 – The Past shifted to multidisciplinary teamwork. Each team selected one artifact for deeper archival research and contextual reconstruction, using mood boards (on MIRO) and narrative reframing of the artifact's historical environment (using museum archives). Sustainability considerations were introduced through the application of contemporary UN SDG lenses to historical contexts. Philosophical concepts related to time, and space were introduced to frame reflection (relativity of time (Eistein, 1920); being, authenticity, & purpose)(Heidegger, 1962), and existence and agency (Sartre, 1993/1943)). Teams engaged in abstraction exercises to extract essential characteristics of the artifact—decoupling function from form—through abstraction and metaphorical reasoning (Henriksen & Group, 2018; Root-Bernstein & Root-Bernstein, 2001). Generative AI tools (ChatGPT, DALL·E, Midjourney, Stable Diffusion–based systems, and more) supported research synthesis, visualisation, and ideation while opening reflection and discussion on ethical guidelines (Boden, 2004; Elgammal, 2020; Shneiderman, 2022).

Act 3 – The Future required teams to transpose the artifact into a speculative sustainable future. Storytelling contextualised the artifact within a future time-space scenario and explicitly linked it to sustainability goals (UN SDGs). Here, storytelling operated not as post-hoc communication but as a generative design engine. Teams developed functional physical or digital prototypes. Generative AI supported rapid visualisation, scripting, and scenario modeling. Peer critiques were conducted in a non-evaluative format (CoP Practice) to promote psychological safety and mutual learning. The iteration culminated in a public Design Day exhibition of artifacts created, integrating narrative, philosophical framing, technical execution, and sustainability positioning.

Across the three acts, storytelling, philosophical reflection, abstraction, technological augmented perception, generative AI, prototyping, peer critique, and public exhibition were intentionally staged to structure the progression from perception to contextualisation to speculative redesign. Through this sequencing, the tools used in Iteration 7 were intentionally staged to support TD collaboration and knowledge creation.

5.5.3 Observe - Iteration 7

5.5.3.1 Overview Data Collected

In this iteration, data were collected from six teams composed of 26 students (9 arts, 8 engineering, 9 DTI; 15 female, 11 male; see Table 47). Across the iteration, 83 individual reflective journals (Journals 1–3) were collected and collated by student, yielding 24 collated individual reflective journals. Journal prompts appear in APPENDIX O. Teams submitted six final reports, produced 12 intermediary prototypes, and delivered six final artifacts. A summary of the final artifacts is provided below; a detailed account of prototype evolution and final artifacts is provided in APPENDIX T. In addition, one researcher reflective journal was collected.

Table 47 Iteration 7 Data Collected

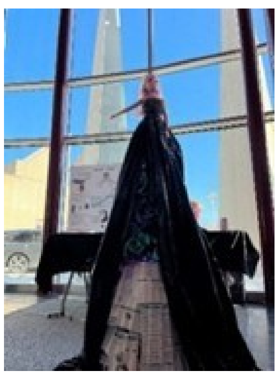
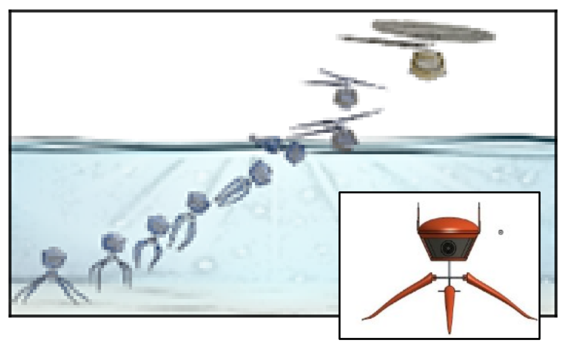
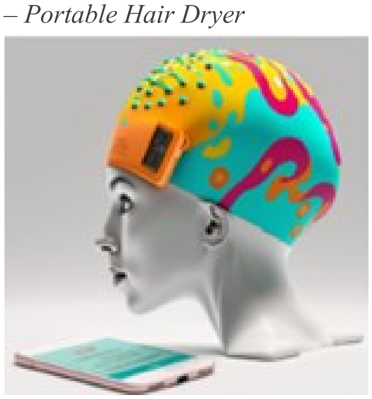
Iteration 7 - Data Collected													
Identification								Individual Data		Team Data			Researcher Data
Iteration	Teams	N Students	A	E	O	F	M	Journals	Collated Journals	Final Reports	Prototypes	Final Artifacts	Journal
7	1	4	2	1	1	4	0	9	3	1	2	1	
	2	4	2	2	0	3	1	14	4	1	2	1	
	4	4	1	1	2	4	0	9	3	1	2	1	
	5	5	2	1	2	3	2	17	5	1	2	1	
	6	4	1	1	2	0	4	18	4	1	2	1	
	7	5	1	2	2	1	4	16	5	1	2	1	
7	6	26	9	8	9	15	11	83	24	6	12	6	1

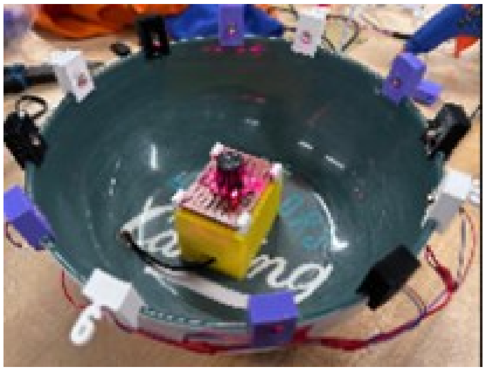
Representative quotations from text-based sources (student reflective journals and final reports), together with critical incidents from researcher observation notes are discussed in the Observational Findings section (Section 5.5.3.3). A summary of the final artifacts is presented next.

5.5.3.2 Artifacts

Across Iteration 7, student teams reinterpreted historical artifacts from the Ingenium collection (seen in Table 48) through speculative, sustainability-driven design, demonstrating how artistic practice can mediate cultural critique, technological innovation, and environmental responsibility. *Team 1- Future Barbie* revisited the iconic doll as both a cultural symbol and a material problem, transforming her into an enlarged, eco-conscious figure that simultaneously challenged gender stereotypes and plastic overconsumption. *Team 2- Biomimic Octo-Suit* reimagined a deep-sea diving suit as an autonomous, biomimetic system, foregrounding sustainable materials and reduced human intrusion to support marine research and conservation. In a more domestic yet equally consequential register, *Team 4- Portable Hair Dryer* project reframed a 1950s Sunbeam artifact into a cordless, energy-efficient bonnet dryer, aligning historical aesthetics with contemporary sustainability and user-centred design. *Team 5- Nostalgia Box* project transformed a century-old Polyphon music box into a speculative, sustainable device for emotional well-being, using music and physical photographs to foster memory, accessibility, and social connection in a dystopian future. Similarly focused on rethinking cultural production, *Team 6- Laser Bowl Instrument* re-envisioned a laser harp as an accessible, low-waste musical interface that reduced material consumption while expanding performative possibilities through light, time, and sound. Finally, *Team 7- Salamander Suit* reinterpreted the heavy Newtsuit as a near-future, eco-friendly diving technology, replacing carbon-intensive materials with sustainable alternatives and emphasising empathy toward both marine ecosystems and human users. Collectively, these projects illustrate how artistic redesign can integrate sustainability, narrative, and material experimentation to reframe existing technologies toward more responsible futures.

Table 48 Iteration 7 Final Artifacts

Team 1 – Future Barbie 	*Team 2 – Biomimic Octo-Suit* 
Team 4 – Portable Hair Dryer 	*Team 5 – Nostalgia* 

Team 6 – Laser Harp	Team 7 – Salamander Suit
	

This summary describes the artifacts created in this iteration; detailed prototype evolution and the final artifacts are provided in APPENDIX T.

5.5.3.3 Observational Findings

The 24 collated individual reflective journals and six final reports were analysed to identify evidence of how the tools introduced in this iteration shaped TD collaboration and TD knowledge creation.

Inductive Thematic Analysis – General Topics Discussed

Based on inductive thematic analysis of the final reports and reflective journals, five cross-cutting themes emerged: (a) sustainability and environmental responsibility, (b) multidisciplinary collaboration and team dynamics, (c) innovation through technology and digital tools, (d) human-centric design and societal impact, and (e) the design process as a reflective journey.

Across projects, *sustainability* functioned not as a constraint but as a generative design ethos, with students repeatedly framing their work as an ethical response to ecological challenges and aligning decisions with systemic impacts and the United Nations Sustainable Development Goals. This commitment is evident in statements such as "*Recognising the problem of plastics waste and misconception of Barbie, we aim to make Barbie as a more sustainable toy," (I7 T1 Final Report)* and *"The current newtsuit… relies heavily on aluminum, which is processed from bauxite, a natural resource that is rapidly being depleted. The need for an alternative that is sustainable has been pressing…" (I7 T7 Final Report)*. Sustainability was thus treated as a concrete driver shaping material choices, production methods, and projected futures. Teams also articulated broader implications, noting, for example, *"Replacing all wooden objects with recycled materials could save around 4 billion cubic meters of wood," (I7 T5 Final Report)* and asserting, *"We believe we should care more about our environment and limit our interference in nature." (I7 T2 Final Report).* These ambitions unfolded within multidisciplinary teams where disciplinary diversity produced both friction and learning.

Students noted logistical challenges—*"One major problem we have encountered multiple times now is scheduling meeting for a time that works for everyone" (I7 T7 Final Report)*—as well as epistemic differences in vocabulary, methods, and expectations. Yet students also described knowledge exchange as multiplicative: *"The interaction of interdisciplinary knowledge, team brainstorming, and the constant innovative thinking have the multiplying effects of knowledge and skills." (I7 T1 S1 DTI Female)* Others emphasised mutual learning through access to teammates' expertise: *"The engineering guys in particular gave us insights into the use of new tools and perspectives some of us on the team weren't familiar with," (I7 T7 S1 DTI Female)* and *"I've also been able to capitalise on their knowledge by asking questions and requesting clarification… This has allowed me to obtain a more in-depth grasp of the content." (I7 T5 S5 DTI Female)*

Technology mediated this collaboration by enabling teams to bridge historical artifacts and speculative futures through modeling, scanning, VR, and AI-supported production workflows. Students reported expanding tool literacy and confidence: *"I managed to pick up some AI tools I have never heard of before," (I7 T5 S5 Art Female)* and *"With the help of this app [Scaniverse], I was able to scan the artifact in the museum for Act-1." (I7 T2 S1 Eng Female)* Teams also used immersive visualisation and video to *"truly capture the historical significance" (I7 T2 Final Report)* of artifacts while reframing them within sustainability narratives.

Technological innovation was frequently coupled with human-centric commitments such as gender equality, accessibility, emotional well-being, and inclusion. For example, Team 1 reported, *"We also used newspaper to deliver messages on gender equality and women's rights… while looking towards the future." (I7 T1 Final Report*) Other teams foregrounded accessibility: *"this addition not only makes the music box more inclusive but also highlights the importance of accessibility in design." (I7 T5 Final Report)* Several projects mobilised nostalgia and memory as design resources, arguing that *"In a world that has lost its sense of connection and meaning, nostalgia may be the one thing that can help us find our way back to each other." (I7 T5 Final Report)*

Finally, students framed design as iterative, reflective practice rather than linear problem solving, consistent with the course's three-act structure. Students noted that *"design is an on-going process that is consistently tested and tweaked to create the best product." (I7 T6 S4 Male)* They also emphasised learning from historical analysis—*"Learning about the past of the artifact helped us to understand its purpose and further explore its application in other areas." (I7 T2 Final Report)*—and valued critique: *"Feedback and criticism can only help you" (I7 T1 S2 Eng Female)*. At its most reflexive, design became a site of identity formation: *"I learned that designing is a deeper way to look at myself. When I look at OctoSuit, I see myself. It shows my character, my abilities, my imagination and my story." (I7 T2 S3 Art Female)*

Researcher's Key Observational Notes

Observation notes documented several critical incidents shaping Iteration 7 and informing subsequent TD-SDT refinements. The museum-based challenge appeared highly motivating, and many students quickly adopted generative AI tools for early assignments. Because widely accessible AI tools had recently entered mainstream use, the teaching team provided explicit instruction on ethical use and permitted AI in course assignments; student reception was positive. Philosophical references related to time and space were introduced to deepen reflection and support conceptual grounding.

Deductive Thematic Analysis for each TD-SDT Tool of this Iteration

This section presents the deductive thematic analysis conducted on Iteration 7's 83 reflective journals and six final reports. Deductive coding was used to identify evidence of each TD-SDT concept/tool pair implemented in this iteration. The analysis followed the Data Coding Framework for Thematic Analysis (Section 5.2) and applied a codebook (APPENDIX F) aligned with the TD Process Assessment Framework dimensions (e.g., trust, mutual learning, conflict handling). This coding approach supported analytical consistency across teams and generated comparable sets of quotations used to substantiate (a) TD process assessments (Section 5.5.3.4) and (b) assessments of the effectiveness of specific concept/tool pairs (Section 5.3.3.5). A complete list of extracted quotations and assessment tables is provided in the accompanying data repository; key excerpts are presented in the Reflect section (Section 5.5.4).

Table 49 Iteration 7 Deductive Analysis of TD-SDT Concept/Tool Pairs

TD-SDT Components Introduced in I7		Number of Quotes per Team						Total
Concept	**Tool**	**T1**	**T2**	**T4**	**T5**	**T6**	**T7**	**I7**
Storytelling	Pixar in-a-box	24	10	19	10	5	7	75
Philosophy	Philo. of Time & Space	4	5	6	10	2	9	36
Abstraction	Analogies/Metaphors	2	2	5	7	2	5	23
Co-creating with AI	Various Generative AI Tools	4	11	18	16	13	6	68
Symbolic Infrastructures	Speculative Futures	10	10	8	11	3	11	53
Total Number of Quotes		44	38	56	54	25	38	255

A complete list of extracted quotes is available in the accompanying data repository. Key excerpts supporting the interpretation of Table 49 are presented in the Reflect section (Section 5.5.4).

5.5.3.4 TD Process Assessment (TDP)

Following the TD Process Assessment methodology described in Section 5.2, team-level scores were derived for each dimension and synthesised into a *TD Process Score* per team Table 50. In Iteration 7, Teams 2, 1,6,4 achieved a high score (7.98, 6.66, 6.65, & 6.18), Team 5 fell in the medium range (4.37). The iteration average was 6.11 (high).

Table 50 Iteration 7 TD Process Assessment

I7 TD Process Assessment Framework					I7 TD Process Assessment					
				I7	T1	T2	T4	T5	T6	T7
TD Process Quality – TD Collaboration			**TPQ Score**	**1.98**	**2.71**	**2.43**	**1.57**	**1.43**	**2.43**	**1.29**
	Collaborative Process	C1- Trust	L/M/H [0,3]	2.33	3.00	3.00	2.00	1.00	3.00	2.00
		C2- Communication		1.67	3.00	2.00	1.00	1.00	2.00	1.00
		C3- Mutual Learning		2.50	3.00	3.00	2.00	2.00	3.00	2.00
		C4- Conflict Handling (Friction)		1.67	3.00	2.00	1.00	1.00	2.00	1.00
		C5- Shared Problem Framing		1.83	2.00	2.00	2.00	2.00	2.00	1.00
	Reflexivity	C6- Equal Footing, Power Relationships & Fairness		2.33	3.00	3.00	2.00	2.00	3.00	1.00
		C7- Team Critical Self-Awareness		1.50	2.00	2.00	1.00	1.00	2.00	1.00
TD Integration Quality – TD Knowledge Creation (Tangible)			**TIQ Score**	**1.30**	**0.94**	**2.56**	**1.61**	**0.94**	**1.22**	**0.50**
	Artifacts Created	K1- Epistemic (Disciplinary) Grounding	L/M/H [0,3]	1.64	1.33	2.67	1.83	1.33	1.67	1.00
		K2- Integration Depth & Coherence		1.58	1.50	3.00	2.00	1.50	1.00	0.50
		K3- Advancement of Understanding (Novelty)		0.67	0.00	2.00	1.00	0.00	1.00	0.00
TD Societal Effects – TD Knowledge Creation (Intangible)			**TSE Score**	**2.83**	**3.00**	**3.00**	**3.00**	**2.00**	**3.00**	**3.00**
	Learning & Capacity Building of Participants	K4- Cognitive, Social & Practical Competencies	L/M/H [0,3]	2.83	3.00	3.00	3.00	2.00	3.00	3.00
	Societal Usefulness	K5- Salient, Credible, Legitimate, Actionable								
	Societal Impacts	K6- Policy & Practices Change								
TD Process Score [0,9] where: Low =[0,2]; Medium=[3,5]; High=[6,9]			**TD Process Score**	**6.11**	**6.66**	**7.98**	**6.18**	**4.37**	**6.65**	**4.79**
			L/M/H [0,9]	**H**	**H**	**H**	**H**	**M**	**H**	**M**

As visually represented by a stacked bar in Figure 19, each team TD Process Score is the sum of the TD Process Quality Score (TPQ), TD Integration Quality Score (TIQ), and TD Societal Effects Score (TSE), each ranging from 0 to 3. The score calculation procedure is described in Section 5.2

and the results are presented here. teams 2,1,6,4 were high scores and Teams 7 & 5 medium scores. With the highest iteration average so far.

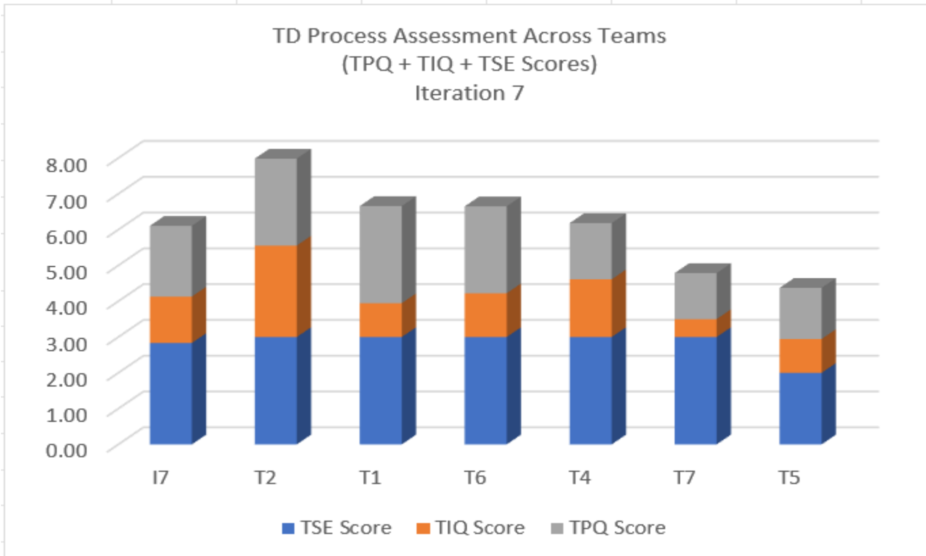


Figure 19 Iteration 7 TD Process Score - TPQ+TIQ+TSE Scores

Figure 20 presents the relative contributions of the C1–C7 dimensions to the overall TD Process Quality (TD Collaboration) score in Iteration 7. Each iteration-level score represents the average of team-level scores and ranges from 0 to 3.

In iteration 7, high contributions were observed for C3-Mutual Learning, C1-Trust C2-Communication and C6-Equal Footing, Power Relationship & Fairness (2.50, 2.33, 2.33). Medium contributions were observed for C5- Shared problem framing, C2-Communication and C4-Conflict handling, C7-Team Critical Self-Awareness (1.83, 1.67, 1.67 & 1.50).

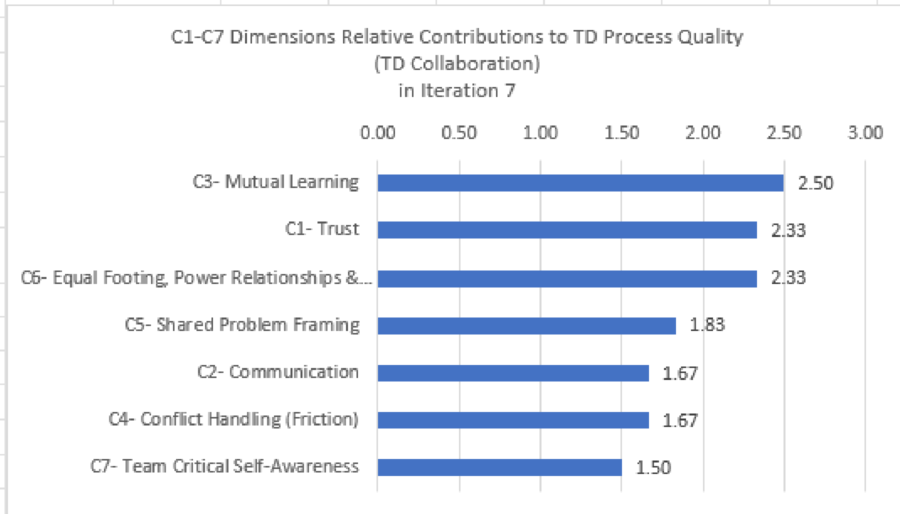


Figure 20 Iteration 7 Relative Importance of Each TD Process Dimension Assessed

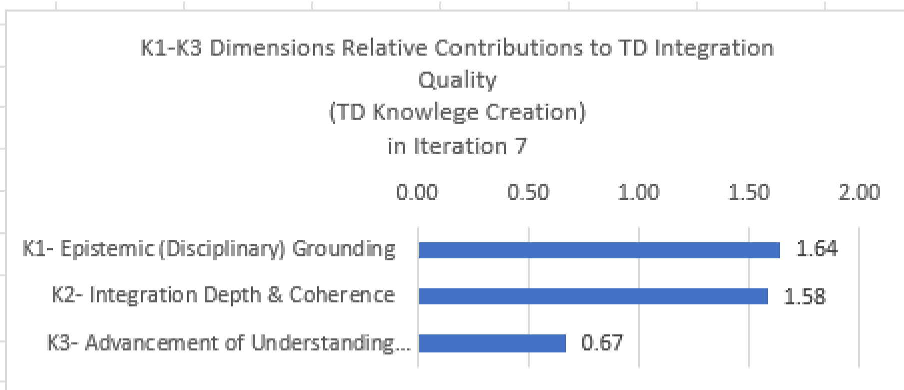


Figure 21 Iteration 7 K1-K3 Relative Contributions to TD Integration Quality (TIQ)

Figure 21 presents the relative contributions of K1–K3 to the overall TD Integration Quality (tangible TD Knowledge Creation) score. As with TPQ, iteration-level scores represent averages of team-level scores and range from 0 to 3.

In Iteration 7: K1-Epistemic Grounding (1.64), K2- Integration Depth and Coherence (1,58) and K3-Novelty/Advancement of Understanding) (0.67).

All three dimensions fell within the lower-to-moderate range, indicating emerging but not yet deep integration across teams. As Iteration 5 provided a comprehensive account of the operationalisation of the TD Process Assessment framework, only the results of this assessment are represented in Table 50.

5.5.3.1 TD-SDT Tool Contribution Assessment

The assessment of TD-SDT concept–tool contributions to TD collaboration and TD knowledge creation draws on the TD Process Assessment dimensions theoretically expected to be activated as explained in Sections 2.6 and 5.2.4.

Deductive Thematic Analysis for each TD-SDT Tool of this iteration

This section applies the same deductive thematic analysis workflow described in **Section 5.2** (and used in Iteration 5 & 6) to identify evidence of how Iteration 7 TD-SDT concept/tool pairs manifested across the TD Process dimensions. Table 51 presents the resulting distribution of tool-relevant excerpts across teams and the iteration.

Table 51 Iteration 7 Deductive Analysis of TD-SDT Concept/Tool Pairs

TD-SDT Components Introduced in I7		Number of Quotes per Team						Total
Concept	Tool	T1	T2	T4	T5	T6	T7	I7
Storytelling	Pixar in-a-box	24	10	19	10	5	7	75
Philosophy	Philo. of Time & Space	4	5	6	10	2	9	36
Abstraction	Analogies/Metaphors	2	2	5	7	2	5	23
Co-creating with AI	Various Generative AI Tools	4	11	18	16	13	6	68
Symbolic Infrastructures	Speculative Futures	10	10	8	11	3	11	53
Total Number of Quotes		44	38	56	54	25	38	255

Assessment of TD-SDT Concept/Tool Pairs

The previous section allowed us to obtain a *TD Process Assessment* for each team within iteration 7, which indicated the level of Transdisciplinarity Collaboration and Knowledge Creation achieved by the team. We now assess the effectiveness of each tool involved in Iteration 7 in supporting the TD Collaboration and Knowledge Creation (or TD Process) level obtained for each team.

Table 52 shows the concept/tool pairs involved in Iteration 7 with their associated mapping (APPENDIX M).

Table 52 Iteration 7 Concept/Tool Pairs Mapping

TD-SDT Components Introduced in I7		TD Process Framework Mapping	
Concept	**Tool**	**TD Collaboration**	**TD Knowledge Creation**
Storytelling	Pixar in-a-box	C3, C2, C5	K2, K5, K4, K3
Philosophy	Philo. of Time & Space	C7, C5, C4, C3	K2, K3, K5, K4
TCS-Abstraction	Analogies/Metaphors	C2, C3, C5	K3 (strong), K2
Co-creating with AI	Various Generative AI Tools	C2,C5,C7, C4,C3	K2, K3, K4
Symbolic Infrastructure	Speculative Futures	C5, C4, C7	K3 (strong), K2, K5, K4

Table 53 presents the assessed values for each dimension of the TD Process Assessment Framework (C1–C7 and K1–K6) for Iteration 7. The first column reports the average score across all evaluated dimensions for this iteration. The subsequent five columns examine the contribution of each focus tool to the overall TD process by assessing its influence on the different dimensions of collaboration and knowledge creation.

Table 53 Iteration 7 TD Process Assessment - Focus Tools

I7 TD Process Assessment Framework				I7	Iteration - Tool Assessment				
				Avearage	Storytelling - Pixar	philo - Concepts	Abstraction - Analogies	Co-Create - Gen AI	Symbolic Infra.- Speculative Futures
TD Process Quality – TD Collaboration			**TPQ Score**	**1.98**	**2.00**	**1.88**	**2.00**	**1.83**	**1.67**
	Collaborative Process	C1- Trust	L/M/H [0,3]	2.33					
		C2- Communication		1.67	1.67		1.67	1.67	
		C3- Mutual Learning		2.50	2.50	2.50	2.50	2.50	
		C4- Conflict Handling (Friction)		1.67		1.67		1.67	1.67
		C5- Shared Problem Framing		1.83	1.83	1.83	1.83	1.83	1.83
	Reflexivity	C6- Equal Footing, Power Relationships & Fairness		2.33					
		C7- Team Critical Self-Awareness		1.50		1.50		1.50	1.50
TD Integration Quality – TD Knowledge Creation (Tangible)			**TIQ Score**	**1.30**	**1.13**	**1.13**	**1.13**	**1.13**	**1.13**
	Artifacts Created	K1- Epistemic (Disciplinary) Grounding	L/M/H [0,3]	1.64					
		K2- Integration Depth & Coherence		1.58	1.58	1.58	1.58	1.58	1.58
		K3- Advancement of Understanding (Novelty)		0.67	0.67	0.67	0.67	0.67	0.67
TD Societal Effects – TD Knowledge Creation (Intangible)			**TSE Score**	**2.83**	**2.83**	**2.83**	**0.00**	**2.83**	**2.83**
	Learning & Capacity Building of Participants	K4- Cognitive, Social & Practical Competencies	L/M/H [0,3]	2.83	2.83	2.83		2.83	2.83
	Societal Usefulness	K5- Salient, Credible, Legitimate, Actionable			0.00	0.00			0.00
	Societal Impacts	K6- Policy & Practices Change							
	TD Process Score [0,9] where: Low =[0,2]; Medium=[3,5]; High=[6,9]		**TD Process Score**	**6.11**	**5.96**	**5.83**	**3.13**	**5.79**	**5.63**
			L/M/H [0,9]	**H**	**M**	**M**	**M**	**M**	**M**

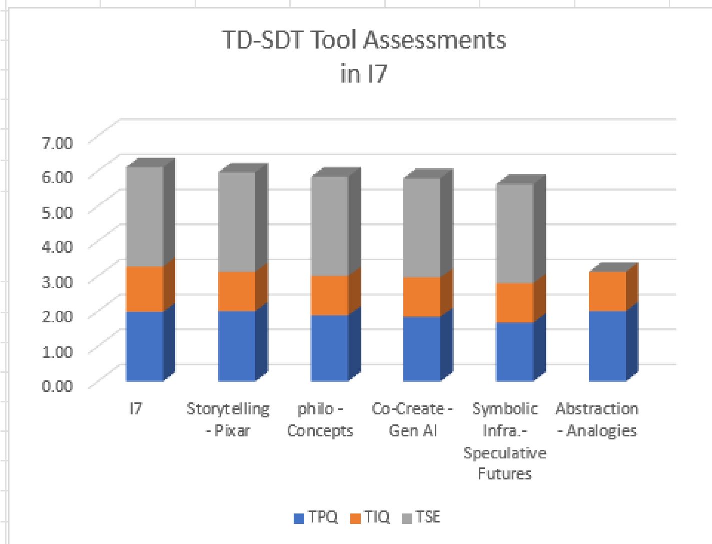


Figure 22 Iteration 7 Tools Assessed Efficiency

The results indicate that, although the overall impact remains within a relatively modest range, several dimensions played a particularly influential role in shaping the TD collaboration score. The four most prominent contributors were *Mutual Learning through Community of Practice (CoP), Trust, Reflexivity through team self-awareness,* and *Conflict handling*, which enabled the productive engagement of friction within the collaborative process.

Artifact Analysis– Team 2: Transformational Creativity through Abstraction

While most teams redesigned their chosen artifacts through variations in materials, aesthetics, or functionality, their concepts remained largely aligned with the original artifact's design logic. In contrast, *Team 2 demonstrated a qualitatively different trajectory characterised by abstraction and conceptual reframing.*

Rather than iterating directly on the diving suit artifact, the team began by analysing the underlying functional and experiential characteristics of the Octosuit. Through sustained observation, discussion, and research into historical diving technologies, the team identified core experiential attributes of the artifact: enabling exploration in environments deprived of oxygen and light, supporting embodied discovery of unknown spaces, and facilitating human curiosity about inaccessible environments.

This process shifted the design reasoning from *artifact-level modification to systems-level interpretation*, consistent with the constructivist and systems thinking dimensions of the Constructivism–Systems Thinking–Complexity (CSC) framework guiding this research. The artifact was no longer treated as a fixed object but as a system of functions and experiences that could be reinterpreted in different contexts.

To support this reframing, the team employed abstraction techniques introduced in the course, extracting essential characteristics from the artifact and representing them through an *abstract boundary object* (Star & Griesemer, 1989). By decoupling these characteristics from the artifact's original form, the team created a conceptual representation that enabled exploration of alternative design directions.

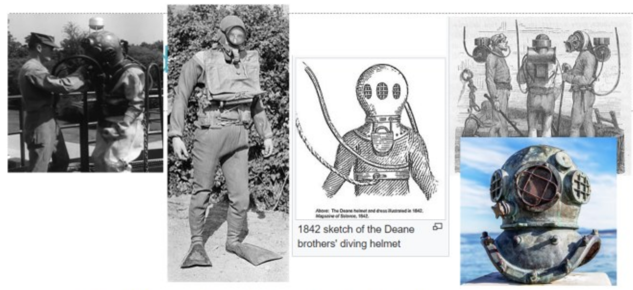
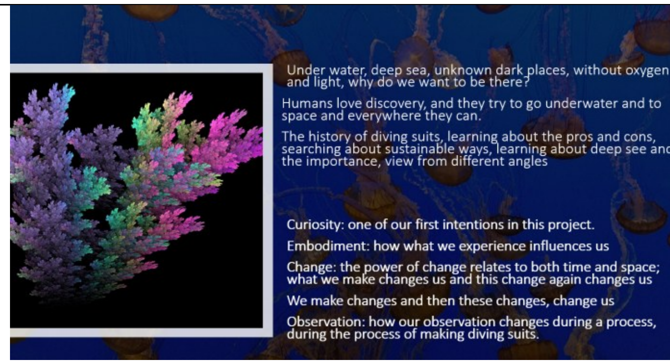
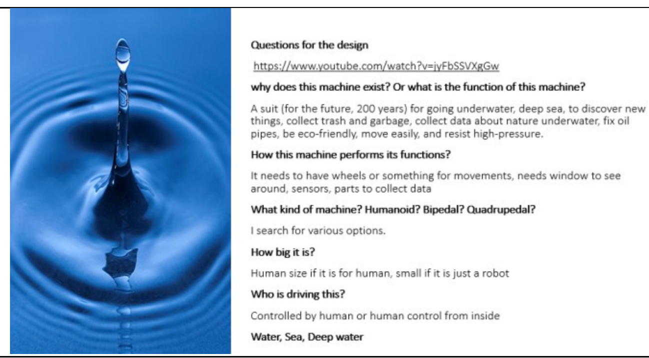
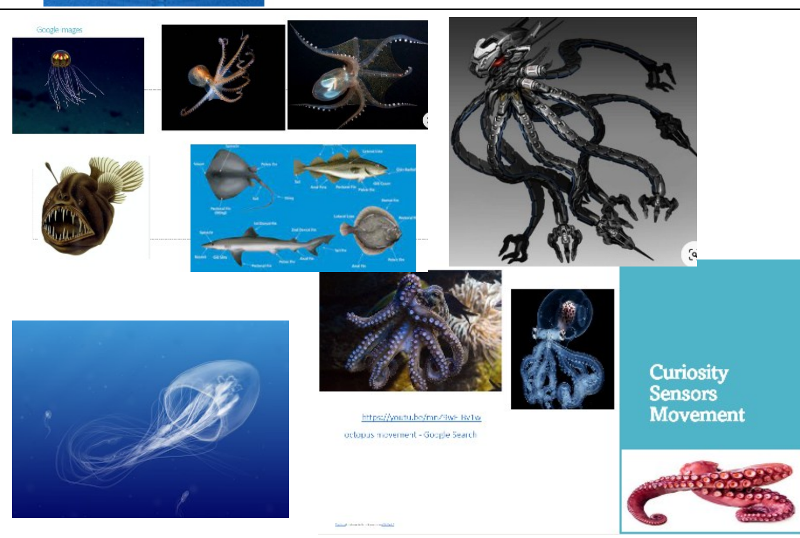
This design trajectory aligns with the notion of *transformational creativity* discussed in Section 2.5.1.3, where innovation emerges not through incremental improvement but through the reconfiguration of underlying conceptual structures (Boden, 2004). Rather than modifying the artifact within its existing design paradigm, Team 2 reinterpreted its fundamental purpose, allowing new possibilities to emerge.

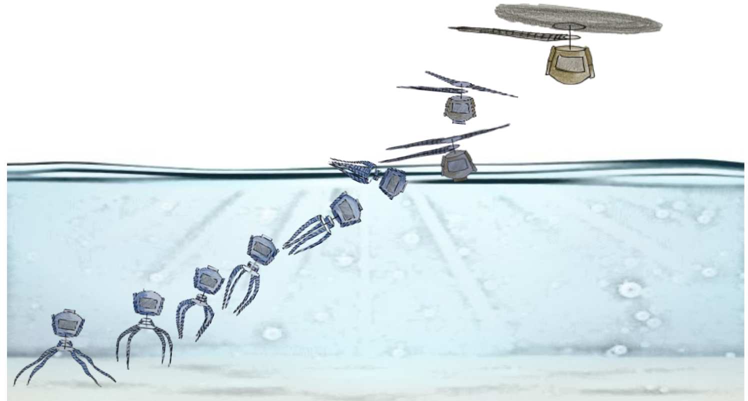
Through this process, abstraction functioned as a mechanism enabling transdisciplinary knowledge creation. By moving from artifact-specific features to underlying experiential and functional principles, the team created a conceptual bridge across disciplinary perspectives while maintaining coherence within the evolving design space.

Team 2's trajectory illustrates how specific TD-SDT mechanisms—abstraction, boundary objects, transformational creativity, philosophical reflection, and extended ideation—can enable transformational design outcomes.

Table 54 Iteration 7 Team 2 TD Knowledge Creation Evolution

The team journey from chosen artifact to their final redesign was not linear and leveraged Time, Space and Philosophy notions seen in class.	

The team researched the design evolution of the Octosuit and similar deep sea diving gear.	 Reference: https://blog.padi.com/history-of-scuba-diving/ https://en.wikipedia.org/wiki/History_of_underwater_diving
They extracted the characteristics they wanted to preserve from their original artifact using deep observation, abstraction, embodied thinking, and more.	
Questioned the design: Why this machine exists? What is the main function? Etc.	
Using divergent thinking and association of characteristics, they explored various concepts and forms.	

The evolutionary transformation shown in the design (moving from underwater robots → hybrid aerial/underwater concept). culminating in a fundamentally reimagined design solution,	

5.5.3.2 Observe Synthesis

Iteration 7 produced the highest TD Process score across all iterations, with strong contributions from mutual learning, trust, communication, and equal footing. These relational conditions supported stable transdisciplinary collaboration.

At the same time, artifact analysis shows that most teams produced incremental redesigns rather than deep conceptual transformations. Team 2 represents the clearest example of transformational TD knowledge creation.

These results indicate that strong TD collaboration does not automatically produce transformational design outcomes. Rather, conceptual breakthroughs depend on specific cognitive and epistemic mechanisms such as abstraction, boundary objects, and philosophical reflection.

5.5.4 Reflect - Iteration 7

5.5.4.1 Key Insights

Iteration 7 provides a nuanced demonstration of the potential—and limits—of the TD STEAM Design Toolkit (TD-SDT) in fostering transdisciplinary (TD) knowledge creation. As evidenced most clearly in Team 2's project, the iteration shows that the TD-SDT can support genuine TD knowledge creation when conditions align. At the same time, the diversity of project outcomes underscores a recurring finding from previous iterations: the presence of a well-designed toolkit does not guarantee TD outcomes.

Each team functions as a unique epistemic configuration, shaped by disciplinary composition, prior experience, values, and group dynamics. TD-SDT operates less as a prescriptive method and more as a collection of enabling ingredients—conditions that *can* support a shift from multidisciplinary coordination to TD integration but cannot ensure it. TD knowledge creation remains contingent, emergent, and unevenly distributed across teams.

Storytelling as a Generative Design Capacity

Analysis of project reports and reflective journals indicates that storytelling functioned as a central epistemic mechanism within the TD-SDT**,** shaping how teams reinterpreted artifacts, integrated disciplinary perspectives, and developed meaningful design directions. Rather than serving as a post-hoc communication device, storytelling operated as a generative design tool, enabling imagination, empathic engagement, and the translation of technical knowledge into accessible narratives.

First, storytelling expanded the conceptual search space by encouraging students to reimagine artifacts beyond their existing form. Teams described narrative as *"the critical part,"* explaining that *"making stories… lets us imagine how far we can go with this item, or how we should rethink this item"* (I7 T2 Final Report). Narrative framing also enabled teams to explore alternative futures for artifacts, as illustrated by Team 1's attempt to let *"Barbie tell her own story and feeling… enabling a holistic overview"* (I7 T1 Final Report).

Second, storytelling supported user-centred and empathic design reasoning. By positioning users as protagonists within narrative scenarios, teams were able to identify challenges and generate design improvements. One team described *"deepening more and more in the user experience story as a protagonist"* and using those insights to guide successive prototypes (I7 T4 Final Report). Reflective journals similarly describe storytelling as enabling perspective-taking and persona development (I7 T7 S1).

Third, storytelling functioned as a boundary-spanning translation mechanism**,** enabling teams to integrate technical information, historical context, and sustainability concerns within coherent narratives. Students described how narrative structures helped communicate complex information through engaging artifacts and multimedia outputs: *"The video… was not only a powerful visual aid but also a dynamic and engaging medium... the video seamlessly blended complex technical information with compelling storytelling to create an unforgettable educational experience."* (I7 T2

Final Report). In several cases, generative AI tools supported narrative construction and scenario development: "*To create a captivating storyline for the artifact, we conducted extensive research on the internet and gained valuable insights to better understand the background and history of the music box. We then brainstormed different ideas and concepts with the help of AI that would be suitable for our artifact before finally settling on a storyline that would revolve around the music box's journey through history."* (I7 T5 Final Report).

Finally, storytelling helped situate artifacts within broader temporal and systemic contexts. By linking artifacts to historical narratives, social change, and sustainability futures, students developed a more systemic understanding of design. One team explained that storytelling provided *"a more macro view – the system"* when positioning characters and artifacts within broader societal narratives (I7 T7 Final Report).

Taken together, these findings demonstrate that storytelling functioned as a core TD-SDT mechanism for transdisciplinary sense-making**.** By supporting imagination, empathy, technical translation, and systems thinking, storytelling enabled teams to move beyond disciplinary perspectives and construct shared narratives around artifacts and future scenarios. Within the TD-SDT, storytelling therefore operates not merely as communication but as a generative epistemic tool supporting TD collaboration and knowledge creation**.**

Abstraction as a Transformative Design Competence

Across project reports and reflective journals, students consistently described abstraction as a key competence enabling them to move beyond literal interpretations of artifacts and access new design possibilities. Rather than functioning as an abstract intellectual exercise, abstraction operated as a practical design mechanism supporting creative exploration, conceptual reframing, and cross-disciplinary integration.

Extracting the Essence of Artifacts.

Students frequently described abstraction as a process of identifying the essential characteristics of an artifact by removing non-essential details. One team defined abstraction as *"the induction of ideas or the synthesis of particular facts into one general theory,"* explaining that it enables designers to *"go to the essence by removing the details that are not essential" (I7 T5 Final Report)*. This process led the team to reconsider the experiential core of their artifact: *"We initially thought about removing all the details and tried to think about the music itself… we tried to think of another* *sense that could be incorporated into the prototype… the visual element from a picture that would trigger some emotion" (I7 T5 Final Report)*. Through this process, abstraction expanded the design problem from single-sense interaction toward multi-sensory experience design.

Decoupling Function from Form.

Abstraction also enabled students to separate an artifact's function from its existing form, opening new design directions. Reflecting on their process, one team recognised that deeper abstraction could have broadened their design space: *"the biggest potential improvement at this stage would have been to internalise the process of abstraction, which would have widened the potential form/uses for the laser technology" (I7 T6 Final Report).* The same reflection noted that abstraction could allow the core function to be *"applied outside of a musical context or re-think the overall shape of the object" (I7 T6 Final Report).* This decoupling of form and function allowed students to reinterpret artifacts in new contexts.

Supporting Cross-Disciplinary Transfer.

Students also described abstraction as a mechanism enabling the transfer of concepts and methods across disciplinary domains. One reflection explained that *"as design is a relatively new discipline… architecture and philosophy are relatively mature disciplines, and many theories can be applied in design abstractly [to provide structure]"* (I7 T7 Eng Male). Others noted how abstraction supported unconventional thinking and perspective-shifting: *"being able to think creatively with abstract thought will help me tackle problems… from a plethora of new angles"* (I7 T7 Eng Male), while abstraction exercises *"challenged us to think outside the box and apply unconventional thinking to our projects"* (I7 T2 Art Male). At the same time, students recognised disciplinary differences in comfort with abstraction and analogies, observing that peers trained in philosophy or literature often *"excelled at applying unconventional thinking,"* while more technical students sometimes *"struggled to adapt to this more abstract approach"* (I7 T2 Art Male). Students observed that while engineering-inclined peers sometimes struggled with the "*abstract approach", those who embraced it were able to excel at "applying unconventional thinking and creating unique solutions to design challenges.*" (T4 S4 Final Report)

Some reflections also highlighted abstraction's role in reasoning and communication. One student noted that *"Logical Intelligence thrives on mathematical models, measurements, abstractions and complex calculations"* (I7 T2 Eng Female), while another emphasised the importance of translating complex ideas into accessible explanations, aiming *"to use 80%+*

laypeople language when explaining abstract concepts… [and] we achieved about 95%" (I7 T1 DTI, Female). Even brief reflections such as *"I appreciate abstract relationships"* (I7 T2 Art Female) underscore abstraction's role in recognising patterns beyond surface detail.

Taken together, these accounts show that abstraction functioned as a generative mechanism within the TD-SDT. By enabling essence extraction, decoupling function from form, and supporting cross-disciplinary transfer, abstraction helped teams move beyond literal artifact redesign toward deeper conceptual exploration and transdisciplinary knowledge integration.

Philosophy Reflection as an Epistemic Scaffold

Across several teams in Iteration 7, students reported that philosophical references and reflective prompts provided intellectual grounding for their design processes. Rather than functioning as abstract theory detached from practice, philosophy shaped how students framed artifacts, imagined design possibilities, and positioned their work within broader human and societal contexts.

Expanding Imagination and Reflexive Thinking.

Philosophical prompts encouraged students to question assumptions and explore deeper meanings embedded in artifacts. Several reflections noted that philosophical frameworks—particularly those associated with Heidegger—directly influenced how students thought about design and existence: *"It should be added that course items and presentations about designing, the philosophy of Heidegger and story items effectively influenced our ways of thinking and imagination." (I7 T2 Final Report).* Lectures discussing abstraction, existentialism, and *"Existence"* prompted some students to reconsider fundamental aspects of life and meaning*:* *"There are lots of concepts seen in class about abstraction, existentialism and Existence that made me question a lot of things in life in general." (I7 T5 DTI Female)* One participant described these reflections as *"philosophical ponderings"* that *"set my soul ablaze," (I7 T2 Art Male)* becoming a powerful source of creative energy and motivation. Through such prompts, students began examining not only artifacts themselves but also their own roles and intentions as designers: *"I learned that designing is a deeper way to look at myself. When I look at OctoSuit, I see myself. It shows my character, my abilities, my imagination and my story."* (I7 T2 Art Female)

In this iteration, students were also invited to reflect on concepts of time and space—past, present, and future—through selected philosophical readings and discussions. One student observed: *"Having a pause/interval within the design process could help us to think more about our* *ideas, make them more realistic or let our creativity go above our consideration by just letting it deepen in our minds."* (I7 T4 Art Female) This created a moment of hesitation and slowing down within the design process, allowing participants to reposition their projects within broader historical and societal narratives rather than treating them solely as technical exercises.

Guiding Conceptual Framing and Design Methodology.

Students frequently applied philosophical frameworks as conceptual tools to guide design exploration. Several teams drew on phenomenology to investigate fundamental human experiences, such as curiosity and discovery or to design environments capable of evoking memory and lived experience.

Teams utilised philosophical inquiry to understand the psychological drivers behind their artifacts. *"We studied different philosophies such as phenomenology, epistemology and constructivism when we asked why people like to go deep down underwater and why humans like discovering new things."* (I7 T2 Final Report).

Phenomenology was applied specifically as a design method to connect the user's history with the artifact's environment. *"The main concepts applied were phenomenology, embodied design and immersive design... the key word I came up with was a design method or environment that evokes memory; then I was inspired by... immersive design, which combines the projection of memory presentation with ontology."* (I7 T7 Eng Male)

Exposure to philosophical methods provided alternative ways to analyze and frame the "problem space" of a project. *"I hope to understand the way of thinking of related disciplines, such as how philosophers think about the topic of time, what relevant methods in the field of philosophy can help me analyze..."* (I7 T7 Eng Male). Students recognized that the established nature of philosophy could provide necessary scaffolding for the developing field of design. *"As design is a relatively new discipline... while architecture and philosophy are relatively mature disciplines, and many theories can be applied in design abstractly [to provide structure]."* (I7 T7 Eng Male).

Supporting Ethical and Systems-Level Reflection.

Philosophical references also helped situate artifacts within broader ethical and systemic considerations by providing frameworks to evaluate environmental responsibility and societal harmony. Students connected Aristotle's natural philosophy to environmental responsibility, noting its emphasis on moderation and respect for nature. *"For example, Aristotle argued that the natural* *world has inherent value and should be treated with respect and moderation, while Confucianism emphasizes the importance of balance and harmony in all aspects of life."* (I7 T5 DTI Female). Confucian philosophy similarly provided a framework centred on balance and harmony, which students linked to sustainable practices. Philosophers *"promote values and principles that are compatible with sustainability, such as minimizing waste, living in harmony with nature, and avoiding excess consumption."* (I7 T5 DTI Male). Political philosophy also informed design narratives: one team drew inspiration from George Orwell's reflections on the control of the past and future to frame their artifact within broader societal dynamics. *"In addition to that, this quote: 'Who controls the past controls the future: who controls the present controls the past' from George Orwell made us think further in our concept where we wanted to connect the past, the present and the future through our Nostalgia box."* (I7 T5 Final Report)

Strengthening Critical Reasoning and Unconventional Problem-Solving

Some reflections further highlighted philosophy's roles in strengthening critical reasoning and unconventional problem-solving. Students noted that peers with philosophical training were often particularly effective at applying abstract reasoning to design challenges. "*The Abstraction and Analogy section revealed how peers with a background in philosophy or literature excelled at applying unconventional thinking and creating unique solutions to design challenges, while those with a more technical background struggled to adapt to this more abstract approach."* (I7 T4 Art Male) Engagement with courses such as *Reasoning and Critical Thinking* helped students learn to "read between the lines" and interpret artifacts in ways that revealed deeper meanings. *"The activity [describing an obsolete telephone] challenged me to think in a way that I am not used to thinking in: reading between the lines and finding different ways to describe what at first appears to be just a simple, obsolete telephone."* (I7 T7 Eng Male) *"I believe that being able to think creatively with abstract thought will help me tackle problems... from a plethora of new angles that would not have been possible before taking this class."* (I7 T5 Eng Male)

Taken together, these accounts suggest that philosophical reflection functioned as an epistemic scaffold within the TD-SDT. By expanding imagination, structuring conceptual inquiry, and grounding ethical reflection, philosophical prompts supported students in moving beyond purely technical problem-solving toward deeper transdisciplinary understanding. Within multidisciplinary collaboration, philosophy therefore operated not as an auxiliary enrichment but as a generative mechanism supporting reflexive and responsible design thinking.

Generative AI as Co-Creative Partner

Iteration 7 also marked a significant expansion in the use of generative AI tools as co-creative collaborators. Students engaged with a broad ecosystem of platforms—ranging from visual generation tools (e.g., Midjourney, DALL·E, Stable Diffusion–based tools) to language, audio, and video systems—to support ideation, storytelling, and rapid prototyping.

Rather than functioning solely as productivity tools, these systems acted as epistemic partners, enabling teams to externalise ideas, explore speculative directions, and democratise creative participation across disciplinary boundaries. AI tools helped equalise contributions by lowering technical barriers and accelerating experimentation, particularly for teams emphasising conceptual and narrative work.

At the same time, their use foregrounded the need for explicit ethical framing. Questions of authorship, bias, sustainability, and responsible use became integral to the design process, reinforcing the importance of embedding ethical reflexivity within AI-supported TD practices.

Transformational Creativity and Conceptual Reframing

The trajectory of Team 2 highlights the role of *transformational creativity within the TD-SDT*. While many teams focused on improving or adapting existing artifact designs, Team 2 engaged in a deeper conceptual reframing process. Through abstraction and boundary-object construction, the team shifted the design problem from modifying a specific artifact to reinterpreting its underlying experiential and functional principles.

This process reflects the form of creativity described by Boden (2004) as *transformational creativity*, in which innovation arises through restructuring the conceptual space itself rather than exploring within an existing design paradigm. Within the TD-SDT framework, such transformations are enabled by mechanisms including abstraction, boundary objects, and sustained epistemic negotiation across disciplinary perspectives.

Importantly, this outcome also illustrates that transdisciplinary knowledge creation does not occur uniformly across teams. While the toolkit establishes enabling conditions for integration, transformational insights emerge contingently through the interaction of tools, team dynamics, and conceptual exploration.

Recognising Conceptual Breakthroughs in Transdisciplinary Design

Iteration 7 also revealed a structural tension between transdisciplinary learning objectives and common evaluation frameworks in design education. While transdisciplinary (TD) knowledge creation often emerges through abstraction, symbolic reasoning, and conceptual reframing, evaluative contexts—particularly public exhibitions or design competitions—tend to privilege tangible, functional prototypes. As a result, projects that prioritise deeper conceptual exploration may receive less recognition despite demonstrating significant epistemic integration.

This dynamic became visible during Design Day, where conceptually ambitious projects—such as Team 2's abstraction-driven redesign of the Octo-Suit—represented strong examples of TD knowledge creation but were less immediately recognisable within evaluation criteria focused on functional novelty and usability. Such conceptual work often requires slower cycles of reflection, abstraction, and reframing, which may temporarily reduce emphasis on physical prototyping.

From a TD-SDT perspective, this observation highlights the importance of evaluation systems that explicitly recognise conceptual integration, abstraction, and symbolic reasoning as legitimate indicators of transdisciplinary innovation. Without such recognition, design environments risk undervaluing the very processes that enable far-reaching and transformative ideas to emerge.

Impact of the Three-Act Design Structure on TD Collaboration and Knowledge Creation

This section synthesises how the three-act pedagogical structure orchestrated the TD-SDT mechanisms introduced in this iteration—including storytelling, abstraction, philosophical reflection, and AI-supported ideation—into a progression that deepened epistemic engagement and supported transdisciplinary collaboration and knowledge creation.

Act 1 (Present) cultivated attentional depth through sensory observation, embodied storytelling, and digital scanning of artifacts. These practices produced early **boundary objects**—such as 3D scans and narrative descriptions—that enabled initial cross-disciplinary exchange even before teams formally collaborated.

Act 2 (Past) introduced multidisciplinary collaboration and contextual analysis. Historical reconstruction and SDG reframing encouraged systems thinking, while philosophical prompts supported reflexive questioning of technological progress and human responsibility. Abstraction exercises expanded the design space by decoupling function from form, and generative AI tools accelerated exploratory ideation.

Act 3 (Future) required integrative synthesis. Storytelling structured speculative redesigns linking sustainability, narrative coherence, and technical feasibility. Prototypes functioned as boundary objects mediating disciplinary perspectives, while non-graded peer critique supported psychological safety and productive epistemic friction. The public exhibition further reinforced integration by requiring teams to communicate philosophical, technical, and sustainability dimensions simultaneously.

Overall, the staged progression strengthened TD knowledge creation by aligning *perception, reflexivity, abstraction, technological mediation, and speculative prototyping within a coherent epistemic infrastructure.* Although Act 1 was completed individually, early tool-sharing and technical collaboration initiated a *community-of-practice dynamic* that supported later transdisciplinary integration.

Synthesis

Iteration 7 demonstrates that storytelling, abstraction, and philosophical reflection significantly strengthened epistemic reflexivity and deepened students' engagement with sustainability challenges. These mechanisms encouraged teams to move beyond functional redesign toward broader conceptual exploration, enabling artifacts to be reinterpreted within historical, societal, and environmental narratives. Co-creation with generative AI further expanded participation and accelerated ideation, while simultaneously highlighting the need for explicit ethical scaffolding when integrating emerging technologies into collaborative design processes.

Across the iteration, several emergent practices became visible. Teams increasingly embraced *abstraction and slowing*, deliberately resisting premature prototyping in favour of reflective conceptual exploration. Artifacts began to function as *boundary objects and symbolic infrastructure*, sustaining multiple disciplinary interpretations while supporting collective sense-making. Generative AI emerged as a provisional co-creative partner, expanding ideation pathways while raising new ethical and epistemic considerations. At the same time, pluralism of perspectives—including intercultural and philosophical approaches to time, space, and sustainability—contributed to richer epistemic diversity within teams.

Iteration 7 also revealed structural tensions between the goals of transdisciplinary learning and external evaluation frameworks. While ungraded peer critique and the exploratory partnership with Ingenium encouraged dialogue and conceptual risk-taking, competitive exhibition contexts tended to privilege functional or visually engaging outcomes. This misalignment highlights the need to reconsider how transdisciplinary learning and knowledge creation are recognised and assessed within educational and public-facing systems.

Compared with previous iterations, teams demonstrated stronger integration depth (K2), more coherent novelty (K3), and increased potential societal relevance (K5). These outcomes suggest that deeper epistemic integration emerged not from any single tool but from the *systemic interaction of relational scaffolding, narrative framing, philosophical reflection, speculative exploration, and symbolic public engagement*. When stabilising structures (coordination, critique, exhibition) interacted with generative tensions (abstraction, philosophical inquiry, AI-supported ideation), teams were better able to negotiate disciplinary differences and construct shared conceptual frameworks.

Overall, Iteration 7 reinforces a central claim of this research: transdisciplinary knowledge creation is not the automatic outcome of a toolkit, but an emergent process shaped by the interplay of relational, conceptual, and symbolic mechanisms within a deliberately designed learning environment.

Emerging TD-SDT Conditions

Taken together, the outcomes of Iteration 7 further clarify the conditions that enable transdisciplinary collaboration and knowledge creation. Effective integration did not arise solely from disciplinary diversity or the presence of creative tools. Rather, it emerged when *epistemic conditions* (such as abstraction, storytelling, and philosophical reflection enabling deeper problem framing), *relational conditions* (including trust, critique, and equitable participation), and *pedagogical conditions* (structured scaffolding, iterative making, and public exhibition) operated together within a coherent learning environment. These interacting conditions helped stabilise collaboration while maintaining the generative tension necessary for conceptual transformation. Their progressive clarification across the iterations informs the consolidation of the Transdisciplinary STEAM Design Toolkit presented in the following chapter.

5.5.4.2 TD-SDT Evolution

Iteration 7 suggests integrating *storytelling, philosophical reflection, abstraction, deliberate slowing, and AI-supported ideation* as core mechanisms within the TD-SDT. Together, these practices supported deeper epistemic reflexivity and enabled teams to move beyond functional redesign toward broader conceptual exploration of artifacts and sustainability futures.

The iteration also highlighted the importance of aligning evaluation structures with transdisciplinary objectives. Competitive exhibition formats tended to privilege functional or visually appealing outcomes, whereas several teams produced *transformational conceptual breakthroughs* that were less easily recognised within traditional judging criteria. Future implementations of the TD-SDT therefore require evaluation frameworks that explicitly value *epistemic innovation, conceptual transformation, and symbolic infrastructures* alongside technical functionality.

More broadly, Iteration 7 demonstrates the potential of the TD-SDT to support *transformational creativity* when conceptual exploration, reflective inquiry, and iterative making are intentionally scaffolded. Continued integration of philosophical inquiry and carefully guided AI-supported creativity—supported by clear ethical guardrails—offers promising directions for further strengthening transdisciplinary knowledge creation in future iterations.

Table 55 Evolution of the TD-SDT - After Iteration 7

TD-SDT Dimensions	Concept	Representative Tools / Practice	Iteration Introduced
Ambiguity	Tolerance for uncertainty	Open challenge: with few constraints (helps creativity)	3-7
Trust	Psychological safety for collaboration	Safe-space creation - create & protect safe-space for vulnerability	3-7
		Informal team building (shared meals, games)	3,4
		Team-level decision making	3,4
Epistemic Reflexivity	Awareness of disciplinary assumptions	Discipline appropriate recruiting / scaffolding	1-7
		ITP Metrics – Personality Types	2,5
		Recognition of epistemic differences (artists focus on *Why*, engineers focus on *How*)	3
		Reflexive prompts – Reflexive Journaling	5-7
		Multiple Intelligences	5-7
Epistemic Humility	Equal participation across disciplines	Equal Footing in collaboration	3-4
		Stereotype deconstruction	4
Epistemic Friction	Productive negotiation of difference	Productive friction, and slowing decision process	3,4

Mutual Learning	Community-based knowledge exchange	Community of Practice	3-7
		Process-driven approach	3,4
		Student-centred approach	3,4
		Team Contract	2-4
		Teach-a-skill	5
Epistemic Boundary Mediation	Boundary Object	Prototypes, shared lexicon, collaborative artifact, Maintain plurality of vision	3-7
	Transformative Creativity	Abstraction & Analogy	7
	Symbolic Infrastructure	Art installation	3,5,7
Enabling Infrastructu re	Project organisation	Design Thinking / Double-Diamond	2-7
		Client / art-client-model	2-5
		Iterative Prototyping	2-7
Art-Studio Pedagogies	Artistic inquiry methods	Object-Based Enquiry	2-7
		Critique (feedback)	2-7
		Exhibit of Artifacts.	2-7
Artistic Exposure	Artistic reference and inspiration	Curated art presentation	2-5
		Artist Talk	3,4
		Storytelling - Artistic Data Visualisation, Visual Narrative	6
		Storytelling - Pixar-in -a-box, Disney Imagineering	7
		Speculative futures	7
Creativity	Perceiving	Formal Analysis	5
	Abstracting	Lego Serious Play	5
	Playing	Lego Serious Play	5
	Modelling	Prototyping	5
	Co-creating	Generative AI	7
Philosophy	Reflections	Concepts for reflections – time & space	7

5.5.4.3 Contribution of Iteration 7 — Consolidation of the TD-SDT Framework

Iteration 7 represents a consolidation phase in the evolution of the TD-SDT, demonstrating how its relational, epistemic, and pedagogical components can operate together within a coherent learning environment supporting transdisciplinary STEAM design. The findings suggest that the interaction of relational conditions, structured process scaffolding, artistic inquiry, and conceptual exploration enabled deeper integration across disciplinary perspectives. This iteration therefore reinforces the TD-SDT as a promising framework for fostering transdisciplinary collaboration and knowledge creation in STEAM education.

5.6 Conclusion – Systematic Assessment and Emerging Patterns

Chapters 4 and 5 together documented the developmental emergence and systematic assessment of the Transdisciplinary STEAM Design Toolkit (TD-SDT). While Chapter 4 traced the exploratory formation of toolkit components through early course iterations, this chapter operationalised the TD Process Assessment Framework and applied it across Iterations 5–7 to evaluate transdisciplinary collaboration and knowledge creation in a structured and comparative manner.

The analysis revealed that transdisciplinary collaboration (C-dimensions) and transdisciplinary knowledge creation (K-dimensions) are related but distinct phenomena. High collaborative process quality—including trust, communication, and equal footing—did not automatically produce deep epistemic integration. Iteration 5 illustrated that strong coordination and mutual learning enabled effective collaboration but often resulted in additive rather than transformative integration.

Comparisons across Iterations 5 and 6 further clarified the role of ambiguity and friction in transdisciplinary work. Ambiguity proved generative only when deliberately orchestrated. In Iteration 6, excessive openness combined with limited technical scaffolding produced confusion and stalled progress. Generative tension without stabilising structures suppressed integration rather than deepened it. By contrast, Iteration 5 demonstrated that bounded ambiguity, supported through symbolic infrastructure, boundary objects, and community-of-practice conditions, enabled abductive reasoning, iterative reframing, and integrative synthesis.

Across Iterations 5–7, deeper integration emerged when coordination mechanisms, reflexive practices, generative tension, and symbolic anchoring operated together. Iteration 7 illustrated how narrative reframing, philosophical inquiry, abstraction, and public exhibition amplified both integrative coherence and societal relevance. These results suggest that integration does not arise from disciplinary diversity alone but from the interaction of relational trust, reflexive repositioning, conceptual restructuring, and symbolic embedding within a structured learning environment.

Throughout these iterations, artistic practices functioned as epistemic and ontological agents within collaboration. Storytelling, speculative design, critique, object-based inquiry, and artistic data visualisation reshaped problem framing, mediated disciplinary differences, and enabled integrative exploration. Prototypes and artworks operated as boundary objects that sustained interpretive flexibility while stabilising dialogue across epistemic communities. In this sense, artistic practices acted not as aesthetic supplements but as epistemic infrastructures supporting transdisciplinary knowledge creation.

Taken together, the findings indicate that transdisciplinary integration is a systemic phenomenon emerging from multiple interacting mechanisms within complex adaptive learning environments. The TD-SDT functioned most effectively when relational conditions, epistemic mechanisms, and pedagogical scaffolding were intentionally aligned.

These results are consistent with the Constructivism–Systems Thinking–Complexity (CSC) framework guiding this research. From a constructivist perspective, knowledge emerged through iterative negotiation of meaning among participants. From a systems thinking perspective, integration arose through interactions among tools, actors, and artifacts within the learning environment. Finally, from a complexity perspective, transdisciplinary knowledge creation unfolded as an emergent property of these interacting conditions rather than as a predictable outcome of any single intervention.

This chapter has therefore made visible the structural conditions under which transdisciplinary collaboration and knowledge creation become assessable. The following chapter synthesises patterns across all seven iterations to articulate a broader explanatory framework for epistemic integration conceptualised as epistemic crossing within complex adaptive systems.

Chapter 6 Consolidating the Transdisciplinary - STEAM Design Toolkit (TD-SDT)

6.1 Introduction – From Iterative Experiments to Framework

This chapter brings together the findings of this dissertation through the articulation of the Transdisciplinary STEAM Design Toolkit (TD-SDT), an original framework developed across seven iterations of action research. While Chapters 4 and 5 traced the progressive evolution of tools, practices, and collaborative dynamics within specific educational contexts, the present chapter shifts perspective: it assembles these empirical insights into a coherent conceptual and operational system.

At the outset of this research was a central question: how can transdisciplinary collaboration and knowledge creation be intentionally supported within STEAM design education? Embedded within this inquiry was a second, more specific proposition—that the arts are not peripheral to this process but can act as catalysts for knowledge creation. Across the iterations, this proposition was not assumed but tested in practice.

The findings demonstrate that bringing disciplines together is not sufficient for TD knowledge creation. Disciplinary co-presence, even when supported by strong collaboration, does not in itself produce integration. Instead, TD knowledge creation emerges under conditions—conditions that enable participants to question disciplinary assumptions, engage with difference, and construct shared conceptual frameworks.

It is within this space that the role of the arts becomes critical. As argued in Chapter 1, artistic practices *expand the epistemic landscape of problem-solving* by introducing alternative modes of perception, imagination, and meaning making. Through narrative, metaphor, abstraction, and symbolic expression, the arts create openings—moments in which established ways of knowing can be unsettled and reconfigured. The empirical findings presented in Chapters 4 and 5 provide evidence of this role in action: artistic practices did not merely enrich collaboration, they actively shaped how problems were framed, explored, and transformed.

Although termed a "toolkit," the TD-SDT does not refer to a fixed set of tools or prescriptive methods. Rather, it is conceptualised as an epistemic infrastructure: a structured configuration of conditions, mechanisms, and practices that can be assembled to support transdisciplinary knowledge creation. Within this infrastructure, tools operate not as isolated techniques, but as activators of deeper epistemic and relational processes.

The dynamics underlying these processes were made analytically visible through the TD Process Assessment Framework (Chapter 5), which distinguishes between *collaborative process quality (C-dimensions) and transdisciplinary integration outcomes (K-dimensions)*. This distinction revealed a critical insight: high-quality collaboration—characterised by trust, communication, and mutual learning—does not necessarily lead to transdisciplinary knowledge creation. Integration requires more than coordination; it requires movement across epistemic boundaries, a movement this dissertation conceptualises as *epistemic crossing*

Through this lens, TD collaboration is no longer understood as an emergent by-product of teamwork, but as a process that can be intentionally cultivated within carefully designed learning environments.

6.2 TD-SDT Framework

The TD-SDT did not emerge as a predefined model. Rather, it developed progressively through iterative cycles of design, observation, and reflection across the seven action research iterations presented in Chapters 4 and 5. Each iteration introduced new tools, refined existing practices, and revealed additional conditions required to support collaboration across disciplinary boundaries. Over time, what began as a set of exploratory interventions coalesced into a structured and coherent system.

Table 56 traces this evolution, documenting how specific dimensions, concepts, and tools were introduced and refined across iterations. It provides a historical account of the toolkit's development and illustrates the cumulative nature of the research process.

Table 56 TD-SDT After 7 Iterations

TD-SDT Dimensions	Concept	Representative Tools / Practice	Iteration Introduced
Ambiguity	Tolerance for uncertainty	Open challenge: with few constraints (helps creativity)	3-7

Trust	Psychological safety for collaboration	Safe-space creation - create & protect safe-space for vulnerability	3-7
		Informal team building (shared meals, games)	3,4
		Team-level decision making	3,4
Epistemic Reflexivity	Awareness of disciplinary assumptions	Discipline appropriate recruiting / scaffolding	1-7
		ITP Metrics – Personality Types	2,5
		Recognition of epistemic differences (artists focus on *Why*, engineers focus on *How*)	3
		Reflexive prompts – Reflexive journaling	5-7
		Multiple Intelligences	5-7
Epistemic Humility	Equal participation across disciplines	Equal Footing in collaboration	3-4
		Stereotype deconstruction	4
Epistemic Friction	Productive negotiation of difference	Productive friction, and slowing decision process	3,4
Mutual Learning	Community-based knowledge exchange	Community of Practice	3-7
		Process-driven approach	3,4
		Student-centred approach	3,4
		Team Contract	2-4
		Teach-a-skill (forma, informal)	5
Epistemic Mediation	Boundary Object	Prototypes, shared lexicon, collaborative artifact, Maintain plurality of vision	3-7
	Transformative Creativity	Abstraction & Analogy	7
	Symbolic Infrastructure	Art installation, exhibition	3,5,7
Enabling Infrastructure	Project organisation	Design Thinking / Double-Diamond	2-7
		Client / art-client-model	2-7
		Iterative Prototyping	2-7
Art-Studio Pedagogies	Artistic inquiry methods	Object-Based Enquiry	2-7
		Critique (feedback)	2-7
		Exhibit of Artifacts.	2-7
Artistic Exposure	Artistic reference and inspiration	Curated art presentation	2-6
		Artist Talk	3,4
		Storytelling - Artistic Data Visualisation, Visual Narrative	6

		Storytelling - Pixar-in -a-box, Disney Imagineering	7
		Speculative futures	7
Creativity	Perceiving	Formal Analysis	5
	Perceiving	Machine emulated senses7	
	Abstracting	Lego Serious Play	5
	Playing	Lego Serious Play	5
	Modelling	Prototyping	2-7
	Synthesising	Integration via journalling	5-7
	Co-creating	Generative AI	7
Philosophy	Reflections	Philo Framing - Concepts for reflections – time & space	7

Table 55 outlines, for each dimension of TD-SDT, the concept it operationalises, its associated tools and practices, and the iteration in which it was introduced or refined. The table`s first row, for example, indicates that ambiguity was introduced in Iteration 3 and subsequently refined across later iterations to cultivate students' tolerance for uncertainty. This was operationalised through open-ended challenges which specify minimal but strategic constraints, encouraging creative problem framing and exploratory solution development. Detailed accounts of these implementations are provided in the Act phase of each iteration in Chapters 4 and 5.

In sum, Table 55 which presents the TD-SDT after seven iterations, functions as a navigational synthesis rather than a prescriptive framework. It enables the reader to trace how conditions and interventions evolved across the research trajectory.

6.3 What the Iterations Revealed About TD Collaboration

This section examines how the TD-SDT operated in practice across the seven iterations. Using the TD Process Assessment Framework to analyse both collaborative process quality (C-dimensions) and integration outcomes (K-dimensions), the analysis identifies recurring patterns in how transdisciplinary (TD) collaboration unfolds.

Across iterations, a consistent dynamic emerged: strong collaboration did not necessarily lead to deep epistemic integration. While teams frequently demonstrated high levels of trust, communication, and mutual engagement, their outcomes often remained conceptually additive rather than transformative. Integration emerged only under specific conditions—when relational stability, epistemic mechanisms, and pedagogical structures interacted within the collaborative environment.

The sections that follow articulate a set of empirically grounded insights that clarify this dynamic. Together, they demonstrate that transdisciplinary knowledge creation is not an automatic outcome of collaboration, but the result of a deliberately configured epistemic infrastructure that enables movement across disciplinary boundaries.

6.3.1 Collaboration Does Not Guarantee Integration

A first insight and one of the most significant findings of this research is the distinction between TD collaboration and TD knowledge creation. As operationalised through the TD Process Assessment Framework (Chapter 5), collaborative process quality (C-dimensions) and integration outcomes (K-dimensions) represent related but analytically distinct aspects of teamwork.

Across iterations, teams demonstrated high levels of collaborative engagement. Trust, communication, and mutual learning were commonly reported, and community-of-practice dynamics emerged as students exchanged skills and negotiated design decisions. These relational conditions supported sustained collaboration and enabled teams to navigate disciplinary differences.

However, such collaboration did not consistently produce deep epistemic integration. Many projects combined disciplinary contributions without transforming their underlying conceptual frameworks, resulting in additive rather than integrative outcomes. In these cases, collaboration stabilised at the level of multi or interdisciplinary coordination rather than advancing toward shared conceptual restructuring, or transdisciplinary integration.

Deeper integration emerged only when relational quality interacted with epistemic mechanisms and pedagogical scaffolding. This distinction highlights a critical insight: while relational conditions are necessary, they are not sufficient to produce TD knowledge creation. Integration depends on additional mechanisms that enable participants to question disciplinary assumptions and construct shared conceptual frameworks.

6.3.2 Key Conditions Enabling TD Collaboration

6.3.2.1 Trust Must Be Cultivated

A second insight emerging from the iterations concerns the role of trust as a foundational relational condition within TD collaboration. Across the seven cycles of this research, the ability of participants to engage in epistemic risk-taking—such as voicing uncertainty, proposing speculative ideas, or working beyond disciplinary expertise—was consistently shaped by the presence or absence of trust. While early implementations often assumed trust as a prerequisite for collaboration, the iterative process revealed that trust must instead be actively cultivated through pedagogical design.

Trust became most visible through shifts in participation and interaction. In early stages, teams frequently exhibited cautious engagement, with students remaining within disciplinary comfort zones and limiting contributions to areas of perceived expertise. As collaboration progressed, and where supportive conditions were established, participants demonstrated increased willingness to share incomplete ideas, question assumptions, and engage with unfamiliar methods. These shifts enabled deeper forms of mutual learning and supported engagement with other core conditions such as ambiguity, friction, and epistemic reflexivity.

The iterative experimentation also revealed that trust is not inherently present nor evenly distributed. In contexts where expectations were unclear, roles were imbalanced, or contributions were perceived as undervalued, trust weakened. These moments often resulted in reduced participation, withdrawal from collaborative processes, or a return to disciplinary silos. In such cases, the absence of trust limited the capacity of teams to engage productively with uncertainty and difference.

Through subsequent iterations, trust was progressively cultivated through targeted pedagogical and relational interventions. Early low-stakes collaborative activities, shared making exercises, and structured opportunities for interaction were introduced to support initial relationship-building. Hands-on and material-based practices—such as rapid prototyping and playful abstraction—proved particularly effective in fostering trust, as they emphasised process over performance and created shared experiences of experimentation. Similarly, critique sessions were reframed as dialogic and exploratory rather than evaluative, allowing ideas to be challenged without undermining interpersonal respect. Transparency in project expectations and assessment criteria further contributed to relational stability by reducing uncertainty around authority and evaluation.

This iterative refinement clarified that trust functions as a productive design condition only when it is intentionally developed over time. It emerges through repeated interactions, shared experiences of uncertainty, and the negotiation of roles and expectations, rather than being assumed at the outset. Importantly, trust does not eliminate disagreement or tension; rather, it enables participants to engage with friction constructively, interpreting critique as part of a shared inquiry process rather than as personal conflict.

Within this dissertation, trust and psychological safety are treated as related but distinct constructs. Trust refers primarily to relational expectations between collaborators, while psychological safety refers to the broader collaborative climate in which participants feel able to engage in interpersonal and epistemic risk-taking. The findings suggest that benevolence-based and competence-based trust contribute significantly to the emergence of psychological safety within transdisciplinary teams. Within the TD-SDT, trust is therefore understood as a relational infrastructure that must be actively designed and sustained. It operates in close interaction with other conditions: ambiguity requires trust to be experienced as an opportunity rather than a threat; friction depends on trust to remain constructive; and epistemic reflexivity relies on trust to make assumptions visible without defensiveness. Taken together, the findings demonstrate that transdisciplinary collaboration depends not only on the presence of diverse perspectives, but on the cultivation of relational conditions that allow those perspectives to be expressed, challenged, and integrated meaningfully.

6.3.2.2 Friction Must Be Cultivated

A third insight emerging from the iterations concerns the role of productive friction within TD collaboration. Across the seven cycles of this research, moments of disagreement, disciplinary tension, and divergent perspectives were not only observed but, in several instances, intentionally surfaced through pedagogical design. Initially, such tensions were often perceived as obstacles to collaboration. Over time, however, they became recognisable as critical moments through which deeper inquiry and integration could occur.

Friction consistently prompted teams to articulate assumptions, negotiate meanings, and reconsider initial approaches. Encounters between differing epistemologies—whether in terms of evaluative criteria, problem framings, or design priorities—required participants to make their reasoning explicit and engage with alternative perspectives. These moments supported processes of epistemic reflexivity and reframing, often leading to more nuanced and integrative outcomes. In several cases, tensions around what constituted “success” (e.g., efficiency versus aesthetic value, feasibility versus speculation) became pivotal in advancing shared understanding.

The iterative experimentation also revealed that friction is not inherently productive. In early or insufficiently supported implementations, friction was sometimes experienced as personal conflict rather than intellectual divergence. When trust was fragile or expectations unclear, tensions led to disengagement, avoidance, or superficial consensus, with teams either withdrawing from disagreement or prematurely converging on safe solutions. In these instances, friction disrupted rather than advanced collaboration.

Through subsequent iterations, friction was progressively reframed and more deliberately cultivated. Pedagogical interventions such as structured critique sessions, boundary objects, reflective dialogue, and the intentional postponement of closure were introduced or reinforced to help teams engage with differences constructively. These mechanisms created conditions in which tension could be externalised, examined, and negotiated, rather than internalised as interpersonal conflict. Boundary objects, in particular, frequently served as focal points for friction, allowing multiple interpretations to coexist and be debated within a shared material or conceptual space.

This iterative refinement clarified that friction functions as a productive design condition only when embedded within a supportive relational environment characterised by trust, psychological safety, and mutual respect. Within such environments, friction operates as a diagnostic indicator of epistemic engagement—signalling that disciplinary boundaries are being encountered and negotiated—rather than as a sign of dysfunction. Its absence, conversely, may indicate superficial collaboration or unexamined dominance of a single perspective.

Within the TD-SDT, friction is therefore understood as a condition that must be actively designed, sustained, and supported. It does not operate in isolation: ambiguity often creates the conditions for friction to emerge; epistemic reflexivity enables participants to interpret it constructively; and pedagogical structures provide the means to work through it. Taken together, the findings demonstrate that friction is not something to be eliminated, but carefully cultivated as a driver of integration, enabling transdisciplinary collaboration to move beyond coordination toward genuine knowledge creation.

6.3.2.3 Ambiguity Must Be Orchestrated

A fourth insight emerging from the research iterations concerns the role of ambiguity within TD collaboration. Across the seven cycles of this research, the deliberate introduction of open-ended design challenges was repeatedly used as a pedagogical intervention to stimulate creative exploration and disrupt conventional problem framings. In early implementations, ambiguity was introduced primarily to encourage experimentation and alternative interpretations. Over time, its role became more clearly understood as a central condition shaping how teams engaged in TD sensemaking.

Ambiguity consistently created space for students to question assumptions, explore multiple directions, and generate unexpected ideas. Faced with ill-defined problems, teams engaged in iterative processes of interpretation and redefinition, often relying on abductive reasoning to move forward. These conditions also appeared to redistribute epistemic authority, as no single discipline could fully define the problem or solution pathway. As a result, ambiguity supported mutual learning and contributed to the emergence of shared conceptual spaces and evolving communities of practice.

At the same time, the iterative implementation revealed important limitations. In several instances—particularly when open-ended challenges were combined with unfamiliar tools or high technical complexity—teams struggled to establish direction. Students reported confusion, repeated restarts, and difficulty converging on coherent approaches. These moments highlighted that ambiguity, when insufficiently structured, could inhibit rather than enable collaboration.

Through subsequent iterations, ambiguity was progressively recalibrated. Rather than being left entirely open, it was intentionally supported through additional pedagogical and relational structures. Interventions such as critique sessions, iterative prototyping cycles, boundary objects, and structured reflection were introduced or reinforced to help teams stabilise their thinking while maintaining conceptual openness. These mechanisms allowed uncertainty to remain present as a generative force, while providing enough guidance to sustain forward movement.

This iterative refinement clarified that ambiguity functions as a productive design condition only when it is carefully orchestrated. It must be balanced with structures that support coordination, sensemaking, and progression. Within the TD-SDT, ambiguity is therefore understood not as an inherent property of complex problems alone, but as a condition that is actively designed, tested, and adjusted through pedagogical intervention.

Taken together, the findings demonstrate that effective TD collaboration does not emerge from openness alone. Rather, it depends on a calibrated interplay between indeterminacy and guidance, where ambiguity creates the epistemic space for exploration, and supporting structures enable that exploration to become coherent, collaborative, and integrative.

6.3.2.4 Epistemic Reflexivity Must Be Cultivated

A fifth insight emerging from the iterations concerns the role of epistemic reflexivity within TD collaboration. Across the seven cycles of this research, the need for participants to critically examine how their disciplinary training, assumptions, and evaluative frameworks shaped their understanding of the problem became increasingly evident. While early implementations included reflective activities, their significance evolved over time, revealing epistemic reflexivity as a central condition for moving beyond parallel disciplinary contributions toward genuine knowledge integration.

Across iterations, moments of epistemic reflexivity most often arose when teams encountered differences in how knowledge was defined, validated, or applied. These moments—frequently triggered by disagreement, uncertainty, or misalignment—prompted participants to articulate implicit assumptions and engage with alternative perspectives. In doing so, students began to recognise that disciplinary approaches are not neutral or universal but situated within specific epistemic and ontological frameworks. This process supported deeper forms of sensemaking, enabling teams to negotiate shared understandings rather than defaulting to unexamined disciplinary positions.

The iterative experimentation also demonstrated that epistemic reflexivity does not emerge spontaneously. In the absence of explicit scaffolding, disciplinary assumptions often remained implicit, leading either to parallel work streams or to the uncritical dominance of a single perspective. In such cases, collaboration appeared coordinated at the surface level but lacked depth of integration.

Through subsequent iterations, epistemic reflexivity was progressively cultivated through targeted pedagogical interventions. Structured reflective prompts, critique sessions, artist talks, and cross-disciplinary dialogue activities were introduced or refined to make epistemic assumptions visible and discussable. These tools created moments of pause within the design process, encouraging participants to reflect not only on what they were producing, but on how and why particular approaches were being privileged. Encounters with artistic practices challenged dominant norms by legitimising alternative modes of inquiry—such as ambiguity, affect, and speculative exploration—thereby expanding the range of epistemic possibilities available to teams.

Empirically, student reflections revealed gradual shifts in perspective across iterations. Participants frequently described moving from initial uncertainty or scepticism toward greater appreciation of other disciplinary approaches. Engineering students, for example, reported increased openness to exploratory and non-linear processes, while art students developed greater awareness of constraints, systems, and feasibility. At the same time, reflexive engagement was not uniformly distributed. Some participants resisted these processes, perceiving them as secondary to task completion or as challenging to disciplinary identity. Rather than being treated as failure, such resistance highlighted sites where epistemic boundaries were actively negotiated.

This iterative refinement clarified that epistemic reflexivity functions as a productive design condition only when deliberately supported. It requires structured opportunities for reflection, dialogue, and comparison, as well as a relational environment in which questioning assumptions is both possible and valued. Without such support, disciplinary perspectives tend to remain implicit, limiting the potential for integration.

Within the TD-SDT, epistemic reflexivity is therefore understood as a condition that must be actively designed and sustained. It does not operate in isolation: ambiguity creates the conditions that prompt questioning; friction surfaces differences that require examination; and pedagogical structures enable these processes to unfold constructively. Taken together, the findings demonstrate that transdisciplinary collaboration depends not only on bringing diverse perspectives together, but on cultivating the capacity to critically engage with how those perspectives are formed, negotiated, and transformed.

6.3.2.5 Community of Practice and Mutual Learning Must Be Cultivated

A sixth insight emerging from the iterations concerns the role of community-of-practice dynamics in sustaining TD collaboration and knowledge creation. Across the seven cycles of this research, collaborative learning did not occur simply through the exchange of disciplinary knowledge, but through the gradual formation of shared practices, mutual engagement, and the co-construction of meaning within teams. While early implementations focused on assembling multidisciplinary groups, the iterative process revealed that sustained interaction was required for these groups to function as cohesive learning communities.

Across iterations, community-of-practice dynamics became visible through the development of shared ways of working. As teams engaged in repeated cycles of making, critique, and reflection, participants began to establish common vocabularies, interpretive frameworks, and criteria for evaluating their work. These shared practices enabled participants to move beyond parallel contributions toward more integrated forms of collaboration, where ideas could be collectively developed and refined rather than simply juxtaposed.

The iterative experimentation also demonstrated that such community dynamics do not emerge automatically from co-presence. In early or weakly structured implementations, collaboration often remained fragmented, with participants working within disciplinary silos and relying on division of labour rather than mutual engagement. In these cases, opportunities for learning across perspectives were limited, and integration remained superficial.

Through subsequent iterations, community-of-practice dynamics were progressively fostered through pedagogical structures that supported sustained interaction. Studio-style approaches—such as informal discussions, iterative critique sessions, and collaborative experimentation with materials and prototypes—created conditions for participants to observe, engage with, and learn from one another's approaches to problem-solving. These repeated interactions allowed students to gradually build familiarity with alternative disciplinary perspectives, not through formal instruction alone, but through participation in shared activity.

Empirically, these dynamics contributed to the expansion of participants' epistemic repertoires. Rather than requiring full mastery of other disciplines, students developed the capacity to meaningfully engage with different forms of reasoning, language, and practice. This process resembles the development of interactional expertise, where participants acquire sufficient understanding of another domain to communicate and collaborate effectively without fully adopting its technical foundations. Over time, this enabled more fluid negotiation of ideas and more integrative design outcomes.

This iterative refinement clarified that community-of-practice dynamics function as a productive condition only when actively sustained through ongoing engagement. They depend on repeated interaction, shared experiences, and opportunities for collective meaning-making, rather than one-time collaboration or task-based coordination alone.

6.3.2.6 Boundary Objects Must Be Cultivated

A seventh insight emerging from the iterations concerns the role of boundary objects in supporting TD collaboration. Across the seven cycles of this research, shared artifacts—such as prototypes, sketches, diagrams, and speculative representations—repeatedly functioned as focal points for coordination and meaning-making across disciplinary boundaries. While initially introduced as practical design tools, their role became progressively clearer as mechanisms enabling teams to engage with epistemic difference without requiring consensus. Within this research, boundary objects are understood as one type of epistemic mediator, contributing to the broader set of mechanisms through which transdisciplinary knowledge creation is enabled.

Across iterations, boundary objects consistently supported collaborative sensemaking by providing shared reference points around which diverse perspectives could be expressed and negotiated. When verbal communication alone proved insufficient—particularly in contexts of disciplinary misalignment—material and visual artifacts allowed participants to externalise ideas, clarify assumptions, and engage in more embodied and situated forms of dialogue. In doing so, boundary objects enabled teams to coordinate action while maintaining epistemic plurality, supporting processes of interpretation, translation, and reframing.

The iterative experimentation also revealed that boundary objects do not function automatically as mediating devices. In early or weakly structured implementations, artifacts were sometimes treated as discipline-specific outputs rather than shared objects for negotiation, limiting their capacity to support integration. In other cases, their interpretive flexibility generated ambiguity around ownership, authority, or decision-making, leading to confusion rather than coordination.

Through subsequent iterations, boundary objects were progressively cultivated as intentional sites of interaction and negotiation. Pedagogical practices such as iterative prototyping, structured critique sessions, and reflective dialogue were introduced or reinforced to ensure that artifacts remained open, provisional, and collectively engaged with. Prototypes emerged as powerful boundary objects, functioning simultaneously as technical explorations, artistic expressions, and conversational devices. Their evolving nature allowed teams to revisit assumptions, surface tensions, and refine shared understandings over time.

Empirically, boundary objects played a critical role in reframing perceived interpersonal conflicts as epistemic differences. By materialising ideas, they enabled teams to shift discussions from subjective positions to shared artifacts, supporting more constructive engagement with disagreement. Iteration 2 provided a clear illustration of this dynamic, where prototypes mediated dialogue between engineering and artistic perspectives, while critique practices supported the development of interactional expertise across disciplinary boundaries. These observations informed the integration of prototyping and studio-based critique as core pedagogical strategies within the TD-SDT.

This iterative refinement clarified that boundary objects function as productive design conditions only when actively engaged as evolving, shared artifacts. Their effectiveness depends not solely on their material form, but on the social practices and interactions that develop around them. When revisited, contested, and iteratively refined, boundary objects support deeper integration and more coherent collaborative trajectories.

Within the TD-SDT, boundary objects are therefore understood as epistemic mediators that link the cognitive, relational, and material dimensions of TD collaboration. They operate in close interaction with other conditions: ambiguity creates the space for multiple interpretations; friction surfaces differences around those interpretations; and epistemic reflexivity enables participants to critically engage with them. Taken together, the findings demonstrate that boundary objects are not merely outputs of collaboration, but essential mechanisms through which teams are able to think together, negotiate meaning, and construct integrative forms of knowledge without requiring epistemic convergence.

6.3.3 Integration Emerges Systemically

The final insight emerging from the iterations is that TD knowledge creation is a systemic phenomenon. Integration did not occur because of any single tool, activity, or intervention. Instead, it emerged through the interaction of multiple conditions within a supportive learning environment.

Across the iterations, deeper integration appeared when relational conditions--such as trust, mutual engagement, and equitable participation--interacted with epistemic mechanisms that expanded how problems and solutions could be understood. Practices such as storytelling, abstraction, speculative design, and philosophical reflection broadened the conceptual space of inquiry, while material practices--prototyping, critique, and public exhibition--provided stabilising structures that anchored collaborative exploration.

Boundary objects frequently mediated this process by translating abstract ideas into shared artifacts, while narrative and symbolic approaches enabled teams to situate their work within broader societal and environmental contexts. When these elements operated together, teams were able to move beyond disciplinary perspectives and construct more coherent and integrative understandings.

This finding reinforces a central claim of this dissertation: TD integration does not emerge from disciplinary diversity alone, but from the deliberate configuration of interacting conditions that support epistemic movement, relational engagement, and sustained inquiry.

6.3.4 Synthesis: Designing Conditions for Epistemic Crossing

Together, the findings presented in this section demonstrate that transdisciplinary collaboration is not a self-organising outcome of bringing disciplines together, but a process that must be intentionally designed and sustained. Across the iterations, friction, trust, ambiguity, reflexivity, community dynamics, and boundary objects each played distinct but interdependent roles in shaping how teams engaged with epistemic difference.

Crucially, these conditions did not operate in isolation. Trust provided relational safety; friction surfaced difference; ambiguity created the space for exploration; reflexivity enabled critical examination; community sustained engagement; and boundary objects mediated interaction. Integration emerged only when these elements interacted within a coherent pedagogical and relational environment.

This synthesis reframes TD collaboration as a dynamic process of epistemic crossing, supported by a configured infrastructure rather than driven by individual tools or disciplinary expertise alone. It is this systemic interplay that enables participants to move beyond coordination toward genuine knowledge creation.

Table 57 consolidates the principal concepts emerging across the iterations and provides operational definitions used in the framework synthesis that follows. The definitions reflect both theoretical foundations and their empirical refinement through the Action Research process.

Table 57 Key Definitions

Key Term	Definition
Epistemic Crossing	The emergent process through which participants move across disciplinary assumptions, perspectives, and modes of knowing to construct new shared understandings. (contribution)
TD-SDT	A configurable epistemic infrastructure, consisting of a set of pedagogical conditions, practices, and mediating tools designed to support transdisciplinary collaboration and knowledge creation. (contribution)
Epistemic Conditions	Conditions which enable participants to question assumptions and explore alternative conceptual framings .(contribution)
Relational Conditions	Conditions which support trust, dialogue, and equitable participation. (contribution)
pedagogical Conditions	Conditions which provide scaffolding, structured processes, and iterative making, (contribution)
Epistemic Mediators	Artifacts, practices, or conceptual mechanisms that facilitate communication, interpretation, and negotiation across epistemic boundaries. (contribution)
Interactional Expertise	The ability to communicate meaningfully and master the conceptual language of a specialist domain without necessarily possessing its full technical or practical competence. Collins (2004)
Boundary Objects	Material or conceptual artifacts that are flexible enough to be interpreted differently by various disciplines while remaining robust enough to maintain a shared identity across those interpretations. Star & Griesemer (1989)
Transformational Creativity	A creative process that occurs when the fundamental generative rules of a conceptual domain are reconfigured, allowing entirely new design possibilities to emerge. Boden (2004)
Symbolic Infrastructure	The shared narratives, cultural scaffolding, and value structures that orient collective perception and embed collaborative insights within broader systems of meaning. Maggs (2024a) ,Vervaeke (2019)

The following sections build on these insights to first rethink the TD-SDT, clarifying how these conditions and mechanisms can be understood, structured, and mobilised as an epistemic infrastructure for TD design.

6.4 TD-SDT Reframed as Epistemic Infrastructure

The empirical trajectory of the seven iterations, examined in the previous section made visible the TD collaboration dynamics. These insights created a shift in understanding of the role of TD-SDT. Table 58 and Table 59 present the reorganised TD-SDT which marks that shift. While earlier iterations foregrounded individual tools and practices, the cross-iteration analysis revealed that TD knowledge creation depends on the interaction of multiple elements operating together. The TD-SDT therefore moves beyond a tool-based perspective and to a system-based perspective. Therefore, the TD-SDT is more accurately understood as an *epistemic infrastructure*—a structure intentionally built to support epistemic activity without prescribing it.

Within this infrastructure, three interdependent components are identified: *conditions, epistemic mechanisms, and tools and practices* (presented in Table 58). *Conditions* define the enabling environment within which collaboration unfolds. *Epistemic mechanisms* describe the processes through which disciplinary knowledge is destabilised, negotiated, and transformed. *Tools and practices* act as *activators*, enabling these mechanisms to operate within concrete educational settings.

The TD-SDT is not intended as a prescriptive method or fixed sequence of steps. Instead, it is best understood as a *configurable epistemic infrastructure* that identifies the conditions, mechanisms, and practices required to support transdisciplinary knowledge creation and clarifies how these elements interact, *but does not predict, guarantee or control the outcome*. In this sense, the term "toolkit" does not refer to a collection of discrete instruments, but to a structured assemblage within which tools gain meaning through their activation of broader epistemic and relational dynamics.

Table 58 presents the TD-SDT focusing on key insights revealed across iterations, highlighting how TD collaboration unfolds and how its underlying dynamics shape processes of knowledge creation. Table 59 presents *Tools and practices* acting as *activators*. Both tables provide a short description of each element, their role within TD-SDT and How and When It Is Used.

Table 58 TD-SDT Core Concepts/ Key Insights

Concept	Short Description	Role within TD-SDT	How and When It Is Used
Enabling Conditions for TD Collaboration			
Relational Conditions			
Trust	Relational safety for epistemic risk-taking	Enables vulnerability, dissent, and speculative contribution	Cultivated early through shared norms, low-stakes making, and transparent expectations
Mutual Learning (or CoP)	Sustained shared engagement	Stabilises collaboration and redistributes epistemic authority	Develops over time through co-making, skill exchange, critique, and collective reflection
Pedagogical Practices - Scaffolding			
Enabling Infrastructure	Project Mgmt - Design Thinking / Double Diamonds	Provides temporal & organisational scaffolding for coordinating collaborations	Introduced at project outset and used throughout
Tools & Practices (also referred to as TD STEAM Tools)			
Listed in table below.			
Epistemic Mechanisms			
Epistemic Reflexivity	Awareness of disciplinary assumptions	Transforms friction into learning and repositioning	Triggered through reflective prompts, critique sessions, and cross-disciplinary dialogue
Destabilisers (Catalysts)			
Ambiguity	Productive indeterminacy in problem framing	Creates epistemic openness; prevents premature closure	Introduced through open challenges at project outset; sustained by resisting over-specification
Friction	Productive epistemic tension	Surfaces differences and activates negotiation	Emerges during critique, conflicting criteria, or reframing; sustained rather than prematurely resolved
Epistemic Mediators			
Boundary Objects	Shared artifacts with interpretive flexibility	Mediate coordination across epistemic differences	Used during sketching, modeling, prototyping, and visualisation phases
Interactional Expertise	Ability to understand and communicate across disciplinary domains without full technical mastery	Enables dialogue, translation, and mutual intelligibility across epistemic boundaries	Developed progressively through critique, collaborative dialogue, and sustained cross-disciplinary interaction; activated when teams must interpret, evaluate, or negotiate ideas originating from other discipline
Transformational creativity	Generative abstractions that expand conceptual space	Propel conceptual transformation beyond coordination	Emerge during ideation, speculative exercises, and metaphor-driven inquiry
Symbolic Infrastructure	Cultural and affective scaffolding for transformation	Anchors epistemic change in shared meaning systems	Cultivated through artistic experiences, narrative framing, and embodied engagement
Epistemic Crossing (Activation of TD-SDT)			
Epistemic Crossing	Structured repositioning across disciplinary epistemic assumptions	Emergent process resulting from interaction of ambiguity, trust, friction, reflexivity, mutual learning and epistemic mediators	Occurs throughout project, especially during friction-mediated negotiation phases.

Table 59 TD-SDT Tools & Practices

Tool	Short Description	Role within TD-SDT	How and When It Is Used
Open Challenge	Minimally constrained design brief	Initiates ambiguity and shared problem space	Used at project launch to destabilise single-discipline framing
Safe Space Creation	Structured relational norms	Builds trust and vulnerability tolerance	Established early; reinforced during critique and tension
Team Social Events	Informal structured interaction	Strengthens relational cohesion	Used at team formation or when friction rises
Equal Footing	Explicit epistemic parity principle	Prevents dominance hierarchies	Stated at outset; revisited during negotiation
Discipline-Appropriate Recruiting	Intentional disciplinary mix	Ensures epistemic diversity	Applied during team formation
Team Contract	Negotiated collaboration agreement	Clarifies expectations and accountability	Created early; revisited if tensions arise
Mutual Learning / Teach-a-Skill	Rotating expert–novice roles	Redistributes authority; builds epistemic crossing	Used mid-project during method/tool exchange
Shared Lexicon Building	Co-created vocabulary	Reduces semantic misunderstanding	Developed early; refined throughout collaboration
Design Thinking / Double Diamond	Divergence–convergence structure	Scaffolds iterative exploration	Used throughout design cycle
Client / Art-Client Model	External stakeholder framing	Grounds design in relational accountability	Introduced during framing and testing phases
Prototyping	Materialised iteration of ideas	Externalises assumptions; mediates negotiation	Used from early ideation through refinement
Studio Critique	Structured peer feedback	Surfaces friction; enables reflexivity	Used at milestone checkpoints
Object-Based Enquiry	Multisensory artifact analysis	Cultivates attentional depth and perception	Used early in research/ideation phase
Formal Analysis (TCS–Perceiving)	Structured observation of form	Develops descriptive precision and epistemic attentiveness	Used during perception exercises
Curated Art Presentation	Exposure to boundary-expanding works	Expands conceptual horizon	Used during ideation and reframing
Artist Talk	Articulated artistic epistemology	Surfaces alternative knowledge regimes	Used during reframing or reflexive sessions
Storytelling (Pixar-in-a-Box)	Structured narrative framing	Bridges affect and design intention	Used mid-project for reframing or presentation
Artistic Data Visualisation	Expressive data representation	Integrates analytical and affective dimensions	Used during synthesis and public exhibition
Speculative Futures	Imagined alternative scenarios	Expands possibility space	Used during ideation and future-oriented reflection
Generative AI as Co-Creator	Computational ideation partner	Introduces epistemic displacement and reframing	Used during speculative exploration
Productive Slowing	Intentional delay of closure	Deepens negotiation and reflexivity	Used when teams rush toward premature convergence

These two tables represent the conceptual change associated with the TD-SDT elements. Next section examines how the TD-SDT functions as an Epistemic infrastructure.

6.5 How the TD-SDT Operates as Epistemic Infrastructure

The diagram below (Figure 23) presents the TD-SDT as epistemic infrastructure: a conceptual and operational model that reconceptualises TD collaboration as a designed epistemic system. Rather than treating collaboration as the simple coordination of disciplinary expertise, the TD-SDT demonstrates that *TD knowledge creation is a structured and cultivable process.*

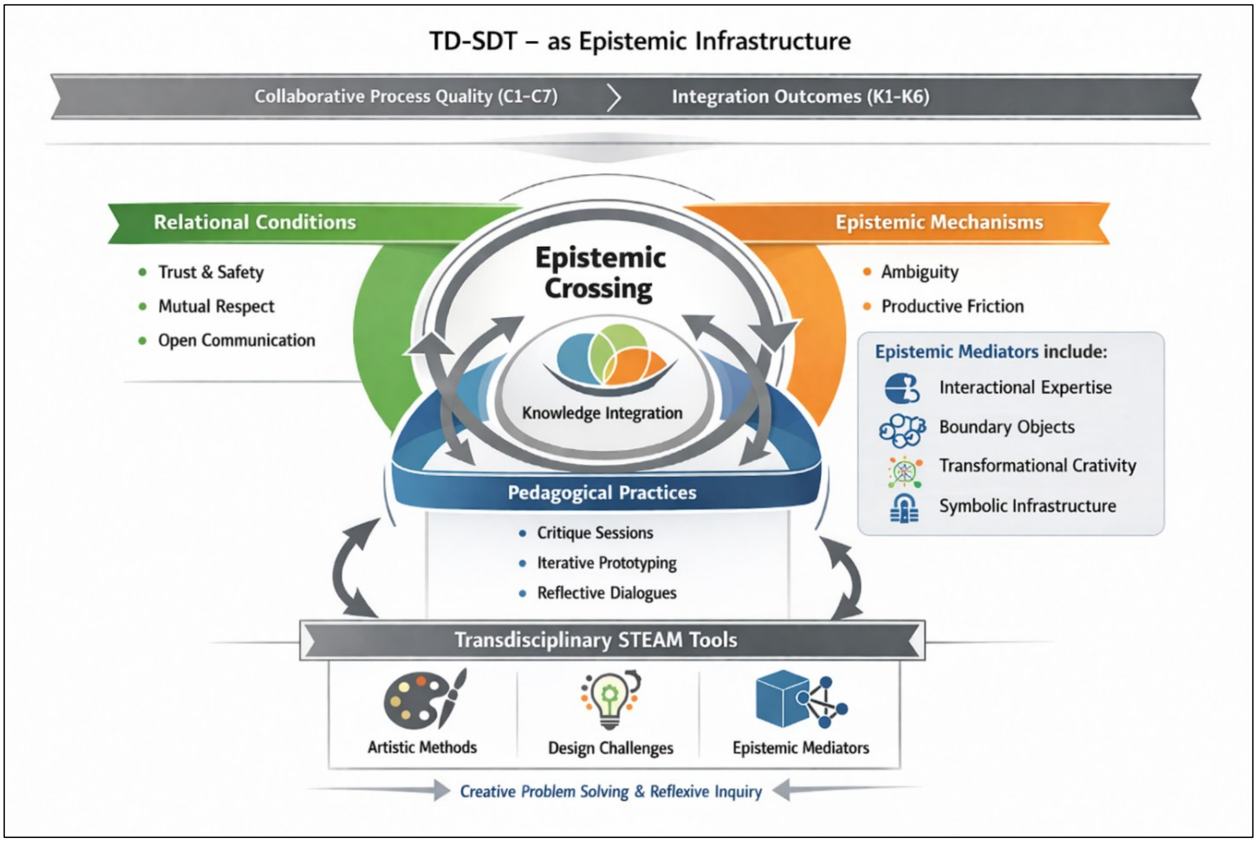


Figure 23 The TD-SDT – as an Epistemic Infrastructure

At the core of this framework is the concept of *epistemic crossing*, introduced in this research to describe the movement through which participants step beyond disciplinary assumptions and co-construct shared conceptual frameworks. In contrast to additive or multidisciplinary approaches, epistemic crossing enables *the transformation of the conceptual space itself*, making genuine integration possible.

The TD-SDT identifies three interdependent layers that must be deliberately orchestrated for this process to occur. *Relational conditions*—including trust, mutual respect, and open communication—establish the social infrastructure required for epistemic risk-taking and sustained engagement with difference. *Epistemic mechanisms*—specifically ambiguity, productive friction, and *epistemic mediators*—drive the destabilisation and reconfiguration of disciplinary perspectives. Within this framework, epistemic mediators (further examined in the following section) constitute a key original contribution, encompassing mechanisms such as boundary objects, interactional expertise, transformational creativity, and symbolic infrastructure, which collectively enable knowledge to move, translate, and transform across epistemic boundaries. *Pedagogical practices*—including critique, iterative prototyping, reflective dialogue, and TD STEAM Tools—provide the structured conditions through which these dynamics can be sustained over time.

These elements are not independent variables but components of an integrated system. The TD-SDT demonstrates that TD integration does not emerge from disciplinary diversity alone, but from the intentional interaction of relational, epistemic, and pedagogical conditions within a designed collaborative environment.

The diagram further articulates the analytical contribution of the TD Process Assessment Framework, which distinguishes between collaborative process quality (C-dimensions) and integration outcomes (K-dimensions). This distinction makes visible a critical empirical finding: high-quality collaboration does not guarantee transdisciplinary integration. Instead, integration emerges only when epistemic mechanisms—particularly ambiguity, friction, and epistemic mediators—are actively engaged and supported.

In sum, the TD-SDT advances a shift from viewing TD collaboration as an emergent by-product of teamwork to understanding it as an *epistemically structured, pedagogically enabled, and systemically orchestrated process*. In doing so, it provides both a theoretical and practical foundation for designing learning environments capable of supporting meaningful TD knowledge creation in STEAM contexts.

Moreover, epistemic crossing is not proposed as a replacement for concepts such as boundary crossing, interactional expertise, or integrative learning. Rather, it functions as a higher-order integrative construct that synthesizes these mechanisms (and others) within a systemic account of transdisciplinary knowledge creation. While existing concepts describe important dimensions of interdisciplinary interaction, epistemic crossing emphasizes the dynamic interplay among ambiguity, reflexivity, symbolic mediation, pedagogical scaffolding, and epistemic negotiation observed within art-inclusive STEAM collaboration.

6.6 Epistemic Crossing Enabled by Epistemic Mediators

TD collaboration requires mechanisms that allow participants to recognise and navigate epistemic boundaries. Epistemic crossing occurs when participants engage with, question, and reconfigure disciplinary assumptions, allowing artifacts and problems to be interpreted through alternative conceptual lenses. Rather than abandoning disciplinary knowledge, participants reposition it within a broader epistemic landscape, progressively constructing shared interpretive frameworks capable of integrating diverse perspectives.

The following section examines the mechanisms through which epistemic crossing occurred within the STEAM design environments analysed in this research. By identifying the processes that expand, destabilise, and stabilise epistemic space, it becomes possible to understand how TD teams transition from multidisciplinary coordination toward deeper forms of conceptual integration.

6.6.1 Mechanisms Enabling Epistemic Crossing

The findings indicate that epistemic crossing emerges through the interaction of multiple mechanisms that expand, destabilise, and stabilise epistemic space. Several of these mechanisms are established in scholarship and are operationally defined in Table 57, while others emerged inductively through the empirical analysis conducted in this research.

Across the iterations, interactional expertise supported communication across disciplinary boundaries by enabling participants to engage meaningfully with the language, assumptions, and priorities of other domains. Boundary objects, including sketches, prototypes, diagrams, and installations, provided shared points of reference through which ideas could be externalised, negotiated, and coordinated despite differing disciplinary interpretations.

The findings also indicate that transformational creativity contributed to conceptual restructuring by enabling participants to reconsider assumptions and reconfigure existing problem framings. Symbolic infrastructure further supported this process by embedding collaborative outputs within broader systems of meaning through narratives, exhibitions, and public representations.

Together, these mechanisms created conditions through which disciplinary knowledge could be negotiated and integrated across epistemic boundaries.

6.6.2 Mechanisms Emerging from the Empirical Findings

While the previous section identified epistemic mediators that structured integration, the empirical analysis also revealed additional cognitive and relational mechanisms that activated and sustained epistemic crossing within collaborative practice.

Across the iterations, abstraction enabled participants to move beyond discipline-specific representations and identify underlying relationships across contexts. Epistemic reflexivity supported critical examination of disciplinary assumptions through reflective practices such as critique, philosophical discussion, and collaborative dialogue.

The analysis also highlighted the importance of productive friction as a mechanism that surfaced differences in assumptions, values, and problem framings. Rather than functioning solely as a source of conflict, friction often stimulated conceptual exploration when supported by trust and structured interaction.

Narrative reframing further expanded the conceptual space of collaboration by encouraging participants to reinterpret challenges through alternative stories, metaphors, and experiential perspectives.

Together, these mechanisms enabled participants to engage with disciplinary differences as resources for conceptual innovation rather than obstacles to collaboration.

Across the iterations, abstraction and narrative reframing expanded conceptual space, productive friction surfaced disciplinary assumptions, epistemic reflexivity enabled critical examination of these assumptions, and boundary objects provided material anchors supporting shared understanding.

Through the interaction of these mechanisms, teams progressively constructed shared conceptual frameworks capable of integrating multiple disciplinary perspectives. Epistemic crossing therefore emerged not as a linear progression but as a dynamic process of conceptual exploration, negotiation, and stabilisation.

Within the TD-SDT, these epistemic mediators and associated mechanisms function as core elements of the broader epistemic infrastructure supporting movement from multidisciplinary coordination toward transdisciplinary knowledge creation.

6.7 Arts as Epistemic and Ontological Catalysts

Across the seven iterations, artistic practices operated as *structural catalysts within the epistemic infrastructure,* shaping how participants engaged across the core dimensions of the TD-SDT.

Artistic practices expanded the epistemic landscape by legitimising indeterminacy, metaphor, and multiple interpretations. artistic practices expanded the space of permissible inquiry, destabilised entrenched epistemic hierarchies, and enabled movement across disciplinary boundaries under conditions of complexity.

Through storytelling, abstraction, critique, and symbolic expression, participants were encouraged to move beyond solution-driven approaches and engage in exploratory sensemaking.

Importantly, artistic practices played a critical role in activating epistemic mechanisms. They sustained ambiguity, transformed friction into productive inquiry, and supported the operation of epistemic mediators by enabling shared interpretation without requiring conceptual closure. In doing so, they contributed directly to epistemic crossing.

These findings support the claim that the arts function not as complementary additions to STEAM collaboration, but as *structural catalysts of epistemic activity*—shaping the conditions under which knowledge can be reconfigured.

This section articulates how artistic practices activated each systemic dimension of the TD-SDT.

6.7.1 Arts and Ambiguity: Legitimising Indeterminacy

Ambiguity is not an accidental feature of transdisciplinary collaboration; it is a necessary condition for epistemic transformation. Artistic practices uniquely legitimise indeterminacy, non-closure, and multiplicity of interpretation. Unlike many technical paradigms that prioritise precision and resolution, artistic modes of inquiry cultivate comfort with open-ended exploration and provisional meaning-making. Therefore, they support ambiguity.

Across iterations, storytelling, speculative design, abstraction, and artistic data visualisation enabled students to dwell within uncertainty rather than prematurely collapsing it. By normalising ambiguity as generative rather than problematic, artistic practices expanded the collaborative problem space. This expansion was essential for epistemic crossing, as it prevented early convergence within disciplinary logics and sustained openness to reframing.

6.7.2 Arts and Epistemic Reflexivity: Surfacing Assumptions

Epistemic reflexivity requires awareness of how knowledge is constructed, legitimised, and constrained within disciplinary systems. Artistic practices catalysed this awareness by introducing aesthetic contrast and metaphorical displacement. Through critique sessions, object-based inquiry, philosophical reflection, and narrative reframing, participants encountered their own assumptions as contingent rather than natural.

The arts functioned as mirrors that rendered invisible epistemic norms visible. By shifting perspective—through metaphor, abstraction, or embodied engagement—students were prompted to interrogate evaluative standards, problem framings, and disciplinary priorities. In this way, artistic practices did not merely support reflexivity; they enacted it.

6.7.3 Arts and Friction: Productive Destabilisation

Friction within transdisciplinary collaboration can either fragment teams or catalyse transformation. Artistic practices introduced forms of productive destabilisation that redirected conflict toward generative exploration. Speculative scenarios, and narrative reframing disrupted defensive disciplinary positioning and encouraged additive co-construction.

Metaphor and abstraction functioned as epistemic attractors—conceptual forms that allowed participants to reconfigure tensions without erasing difference. Rather than resolving friction through compromise, artistic practices transformed it into epistemic movement. This productive destabilisation was critical to preventing collaboration from remaining at the level of procedural coordination.

6.7.4 Arts and Community of Practice: Normalising Critique and Iteration

Studio-based pedagogies introduced cultural norms of iterative critique, vulnerability, and revision. In artistic communities of practice, feedback is not evaluative closure but developmental dialogue. This orientation shifted collaborative culture across STEAM teams, reducing defensiveness and fostering mutual learning.

By embedding critique as routine rather than exceptional, artistic practices cultivated epistemic humility and equal footing. Participants moved from defending disciplinary authority toward coauthoring emergent knowledge. The studio model thus provided relational scaffolding essential for sustained epistemic crossing.

6.7.5 Arts and Boundary Objects: High-Flexibility Mediation

Artistic artifacts—prototypes, installations, sketches, visual narratives—operated as high-flexibility boundary objects. Their interpretive flexibility allowed multiple disciplinary readings while maintaining shared reference. Unlike purely technical representations, these boundary objects often preserved ambiguity, thereby sustaining dialogue rather than prematurely fixing meaning.

By externalising ideas into aesthetic forms, these artifacts stabilised collaboration long enough for deeper negotiation to occur. In systemic terms, these boundary objects functioned as stabilisers within complex adaptive systems: sufficiently robust to coordinate action, yet sufficiently elastic to accommodate epistemic plurality.

6.7.6 Arts and Symbolic Infrastructure: Embedding Meaning

At the deepest systemic level, artistic practices contributed to symbolic infrastructure. Through public exhibition, narrative framing, and embodied engagement, projects became embedded within shared cultural meaning systems. Art translated abstract systems—climate data, technological infrastructures, sustainability metrics—into experiential encounters.

This symbolic embedding reshaped how participants related to problems and to one another. Rather than treating collaboration as task execution, artistic framing reoriented it toward collective sense-making within complex systems. In doing so, artistic practices altered not only what was produced but how meaning was constituted.

6.7.7 Structural Claim

Across all six core dimensions of the TD-SDT, artistic practices functioned as structural mechanisms supporting epistemic movement rather than as supplementary enhancements. Across the iterations, they contributed to ambiguity tolerance, reflexive awareness, productive engagement with friction, negotiation through epistemic mediators, collaborative culture, and the embedding within symbolic systems.

These findings suggest that artistic practices operated as epistemic infrastructure within TD collaboration. Rather than serving only expressive or aesthetic purposes, they supported participants in navigating epistemic difference, systemic interdependence, and emergent complexity in ways that procedural coordination alone was insufficient to sustain.

The findings therefore provide empirical support for the broader claim introduced in Chapter 1 regarding the role of the arts in STEAM environments. Rather than reasserting a theoretical position, the iterations demonstrated how artistic practices functioned structurally within collaborative processes and contributed to conditions supporting epistemic crossing and knowledge creation.

The significance of this structural role appeared strongest in contexts characterised by high epistemic diversity, open-ended problem framing, limited interactional expertise, and the absence of established integrative infrastructures. Under such conditions, artistic practices operated as primary epistemic infrastructure, supporting collaboration and knowledge creation. In contexts where stronger integrative infrastructures already exist, they appeared to function more as complementary or amplifying epistemic mediators.

6.8 Interpreting the TD-SDT Through the Constructivism–Systems Thinking–Complexity (CSC) Framework

The TD-SDT, while emerging from empirical experimentation, can be interpreted through the Constructivism–Systems Thinking–Complexity (CSC) framework. As established in Section 1.3, CSC provides the conceptual foundation for understanding transdisciplinary collaboration as an adaptive process of knowledge creation. Rather than rearticulating the framework's theoretical foundations, the present findings demonstrate how these principles became operationalised through the toolkit and its implementation across iterations.

From a constructivist perspective, the findings indicate that knowledge creation occurred through collaborative meaning-making rather than through the transfer or accumulation of disciplinary knowledge. Across the iterations, participants developed new understandings through interactions with artefacts, negotiation of disciplinary assumptions, and reflective practices such as storytelling, abstraction, and critique.

From a systems thinking perspective, the findings suggest that transdisciplinary integration emerged through relationships among participants, tools, artefacts, and learning contexts rather than through isolated interventions. The toolkit therefore functioned as an interconnected structure in which epistemic, relational, and pedagogical conditions operated together to support collaboration.

From a complexity perspective, the findings demonstrate that collaborative processes remained adaptive and emergent despite intentional pedagogical scaffolding. While the TD-SDT provided structures supporting epistemic crossing, outcomes continued to develop through iterative exploration, productive friction, and evolving interactions across teams and contexts.

Interpreted through the CSC framework, the TD-SDT therefore functions not as a deterministic method but as an enabling infrastructure that creates conditions supporting epistemic crossing and transdisciplinary knowledge creation.

6.9 Conclusion – The TD-SDT as Epistemic Infrastructure

This chapter has consolidated the findings of this dissertation through the articulation of the TD-SDT as an epistemic infrastructure for transdisciplinary collaboration and knowledge creation. It demonstrates that integration does not emerge from disciplinary diversity or collaboration alone, but from the deliberate configuration of interacting conditions, mechanisms, and practices.

A central finding is the distinction between collaboration and integration. While teams often achieved high levels of trust, communication, and mutual engagement, these relational qualities did not in themselves produce TD knowledge. Integration emerged only when relational conditions interacted with epistemic mechanisms—particularly ambiguity, productive friction, epistemic reflexivity, and epistemic mediators—within structured pedagogical environments. Transdisciplinary collaboration must therefore be intentionally designed rather than assumed.

Within this process, *epistemic crossing* provides a unifying lens, describing how participants question and reconfigure disciplinary assumptions to construct shared conceptual frameworks. This process is systemic rather than linear, emerging through the interplay of destabilising forces, reflexive practices, and stabilising mechanisms such as boundary objects and symbolic infrastructures.

A key contribution of this research is the concept of *epistemic mediators*, which identifies how knowledge moves, translates, and transforms across epistemic boundaries. By bringing together interactional expertise, boundary objects, transformational creativity, and symbolic infrastructure, and extending these with empirically grounded mechanisms such as abstraction, narrative reframing, and productive friction, the research clarifies how epistemic crossing is both structured and enacted in practice.

The chapter also reframes the TD-SDT itself. Rather than a prescriptive toolkit, it is a configurable epistemic infrastructure composed of enabling conditions, epistemic mechanisms, and activating tools and practices. Tools gain meaning through their role in activating deeper epistemic and relational dynamics, supporting integration without determining outcomes.

Crucially, the findings establish the arts as structural components of this infrastructure. Artistic practices function as epistemic and ontological catalysts, expanding conceptual space, legitimising ambiguity, transforming friction into inquiry, and embedding knowledge within symbolic systems. They are not complementary additions, but conditions for epistemic movement.

Interpreted through the Constructivism–Systems Thinking–Complexity (CSC) framework, the TD-SDT is best understood as an enabling system: knowledge is co-constructed, integration emerges from relational and systemic interaction, and outcomes remain adaptive and unpredictable.

This chapter reframes TD collaboration as an epistemic process that can be intentionally designed. The TD-SDT provides both a conceptual model and a practical framework for cultivating the conditions under which TD knowledge creation can emerge in STEAM education.

The following chapter builds on these insights to articulate the contributions and implications of this research.

Chapter 7 Conclusion

7.1 Introduction

This dissertation set out to investigate how transdisciplinary collaboration and knowledge creation can be intentionally supported within STEAM learning environments. Through seven iterative course implementations conducted over multiple years, the research examined how engineering and visual arts students engaged in collaborative design processes and how specific pedagogical interventions influenced the depth of interdisciplinary integration achieved.

The findings demonstrate that assembling students from multiple disciplines does not produce transdisciplinary collaboration. Instead, meaningful integration emerges when learning environments are intentionally structured to support epistemic movement across disciplinary perspectives. Across the iterations analysed in this research, such movement occurred when collaborative environments combined open-ended design challenges, artistic inquiry, reflective dialogue, and material exploration through shared artifacts.

Building on these findings, the dissertation identifies epistemic crossing as a central process through which participants negotiated disciplinary assumptions and constructed shared spaces for collaborative inquiry. The findings further indicate that artistic practices supported this process by expanding conceptual exploration and mediating disciplinary differences.

These insights are synthesised in the *Transdisciplinary STEAM Design Toolkit (TD-SDT)*, an epistemic infrastructure that integrates epistemic, relational, and pedagogical conditions with collaborative design processes and artistic practices to support transdisciplinary knowledge creation. The following sections outline the theoretical, methodological, and pedagogical contributions of this research and discuss their implications for STEAM education and transdisciplinary collaboration more broadly.

7.2 Contributions of the Research

By synthesising insights generated across seven iterative course implementations, this dissertation contributes to the emerging field of transdisciplinary STEAM design education in three primary ways. First, it advances a theoretical account of explaining mechanisms that support transdisciplinary knowledge creation. Second, it introduces a methodological framework for assessing collaboration and knowledge creation. Third, it develops the Transdisciplinary STEAM Design Toolkit (TD-SDT), a pedagogical framework supporting transdisciplinary learning.

Together, these contributions deepen understanding of how transdisciplinary collaboration can be intentionally designed, facilitated, and assessed within STEAM learning environments. The following sections elaborate each contribution in greater detail.

7.2.1 Theoretical Contributions

This research advances theoretical understanding of how transdisciplinary knowledge creation emerges within STEAM learning environments by conceptualising the processes through which disciplinary knowledge can move, interact, and transform. The findings demonstrate that disciplinary diversity alone does not produce meaningful integration. Rather, integration emerges through mechanisms that enable participants to move beyond disciplinary boundaries and construct shared conceptual spaces.

Epistemic Crossing

The findings identify epistemic crossing as a central process underlying transdisciplinary collaboration and highlight several mechanisms that support movement across disciplinary perspectives, including epistemic mediators and reflective practices. The study identifies several mechanisms that support this process. These mechanisms collectively explain how teams moved beyond multidisciplinary coordination toward deeper conceptual integration.

Arts as Epistemic Catalyst

A second contribution concerns the empirical identification of artistic practices as structural components within collaborative processes. Across the iterations, practices such as storytelling, critique, abstraction, and speculative exploration supported reframing, reflexivity, and conceptual transformation. In this sense, the arts contribute not only creative expression but also foundational epistemic capacities that support transdisciplinary knowledge creation.

Conditions for Epistemic Crossing and TD Knowledge Creation

The findings further clarify that productive transdisciplinary collaboration depends on interacting epistemic, relational, and pedagogical conditions rather than isolated interventions.

7.2.2 Methodological Contributions

This research also contributes a methodological framework for assessing transdisciplinary collaboration and knowledge creation.

TD Process Assessment Framework (C & K Dimensions)

The TD Process Assessment Framework**,** developed and operationalised in Chapter 5, provides a structured approach for analysing the dynamics of transdisciplinary teamwork. The framework distinguishes between two sets of dimensions: Transdisciplinary collaboration dimensions (C-dimensions)**,** which capture relational and process-oriented aspects of teamwork such as trust, communication, and mutual learning, and Transdisciplinary knowledge creation dimensions (K-dimensions), which capture epistemic grounding, integration depth, novelty, and societal relevance.

Distinguishing these dimensions reveals an important empirical finding of this research: high-quality collaboration does not necessarily produce deep epistemic integration.

Through rubric-based scoring, artifact analysis, and qualitative evidence from student reflections and reports, the framework enabled systematic comparison across teams and iterations. This methodological approach made it possible to identify patterns in collaboration and integration and to evaluate how specific pedagogical interventions influenced transdisciplinary processes.

The TD Process Assessment Framework therefore offers a *replicable method* for researchers and educators seeking to study or evaluate transdisciplinary collaboration in educational contexts.

7.2.3 Pedagogical Contributions

TD-SDT

The primary pedagogical contribution of this research is the development of the TD-SDT**.** Rather than prescribing a fixed sequence of activities, the toolkit provides a structured framework that integrates relational, epistemic, and pedagogical conditions to facilitate transdisciplinary collaboration and knowledge creation.

Drawing from design thinking, studio art pedagogies, and transdisciplinary collaboration practices, the TD-SDT integrates pedagogical mechanisms shown across the iterations to support epistemic crossing and collaborative knowledge creation.

Importantly, the findings also indicate that artistic practices occupy a central role within this pedagogical architecture. By supporting ambiguity tolerance, symbolic exploration, and reflective inquiry, artistic approaches facilitate the conceptual transformations required for transdisciplinary knowledge creation.

The TD-SDT therefore provides a practical and adaptable framework for designing STEAM learning environments that move beyond multidisciplinary coordination toward deeper forms of transdisciplinary integration.

The transferability of the TD-SDT is likely to operate more strongly at the level of epistemic principles than through exact institutional replication. While the implementation described in this dissertation benefited from enabling conditions, such as artistic partnerships, makerspaces, and intensive facilitation, the underlying functions--including epistemic mediation, ambiguity negotiation, reflexive dialogue, and integrative scaffolding--may be enacted through alternative structures adapted to local institutional contexts.

7.3 Implications of the Research

The findings of this dissertation have implications for both STEAM design education and the broader study of transdisciplinary collaboration. These implications concern how collaborative learning environments are designed, how epistemic integration is supported, and how the role of the arts within STEAM initiatives is conceptualised.

7.3.1 Implications for STEAM Design Education

First, ambiguity should be intentionally designed rather than minimised. Open-ended challenges are not signs of weak instructional planning but mechanisms that activate epistemic exploration and encourage participants to question disciplinary assumptions.

Second, friction should be reframed as diagnostic rather than disruptive. Moments of tension often signal engagement with epistemic difference and can stimulate conceptual reframing when supported by appropriate relational conditions.

Third, artistic and speculative practices should be embedded as central learning mechanisms rather than peripheral activities. Practices such as storytelling, object-based inquiry, critique, abstraction, and speculative design expand the epistemic repertoire of participants and strengthen their capacity to engage with complex and uncertain problem spaces.

Fourth, assessment frameworks must attend to collaborative process quality and integration depth, not only final outputs. Without process-sensitive evaluation, claims of transdisciplinary collaboration risk remaining superficial or purely additive.

Taken together, these implications suggest a shift from efficiency-driven design education toward epistemically generative learning environments that prioritise reflexivity, exploration, and integrative knowledge creation.

7.3.2 Implications for Transdisciplinary Research

Beyond educational contexts, this research also contributes to the broader field of transdisciplinary research.

First, the research provides a conceptual framework for understanding how transdisciplinary collaboration can be intentionally structured and supported.

Second, the TD Process Assessment Framework offers a structured approach for evaluating transdisciplinary collaboration and knowledge integration. Although developed within educational contexts, the framework may be adaptable to collaborative research and innovation teams addressing complex societal challenges.

Third, the findings reposition arts-based practices as systemic enablers of epistemic crossing. Artistic inquiry expands conceptual exploration, supports reflexive dialogue, and enables participants to reframe problems across disciplinary boundaries.

In this sense, the TD-SDT functions not only as a pedagogical toolkit but also as a conceptual model for structuring transdisciplinary collaboration in research and innovation environments.

7.4 Assumptions, Limitations, Threats to Validity and Transferability

While this research provides empirical and conceptual insights into transdisciplinary collaboration within STEAM design education, several assumptions, limitations, threats to validity, and considerations regarding transferability should be acknowledged. These considerations relate to the contextual scope of the study, the methodological characteristics of Action Research, and the boundaries within which the findings should be interpreted.

7.4.1 Assumptions

Several assumptions underlying this research should be acknowledged. The dissertation assumes that transdisciplinary collaboration benefits from epistemic diversity, reflexive dialogue, ambiguity tolerance, and iterative negotiation across disciplinary perspectives. While these assumptions are strongly supported by both the literature and the findings of this study, alternative collaborative contexts may prioritise efficiency, standardisation, disciplinary specialisation, or hierarchical decision-making differently. Consequently, the mechanisms and conditions identified in this research should not be interpreted as universally optimal for all forms of collaboration.

7.4.2 Limitations

First, the research was conducted within a single institutional context. The STEAM design courses examined were implemented within one university environment and involved students primarily from engineering, arts, and related interdisciplinary programmes. While the iterative course design enabled observation of collaborative dynamics across multiple iterations, broader validation across institutions and cultural contexts would strengthen the generalisability of the findings.

Second, the study was conducted within educational environments and projects constrained by the timelines of academic courses. While this context provided valuable insights into transdisciplinary learning processes and epistemic collaboration in higher education, the dynamics of longer-term collaborations within professional organisations, industry teams, policy environments, or highly regulated technical settings may differ. In particular, the long-term effects of transdisciplinary STEAM learning—such as impacts on professional identity formation, sustained collaborative practices, and the evolution of epistemic interactions over time—were not examined beyond course completion. Further research is therefore needed to assess the transferability and longer-term applicability of the framework in professional contexts.

Third, the TD Process Assessment Framework developed in this research provides a structured approach for analysing collaboration and integration, yet the assessment process remains interpretive and partly qualitative in orientation. Although triangulation, structured rubrics, repeated cross-iteration comparison, and reflexive analysis were used to strengthen interpretive credibility, the framework was not designed as a statistically validated measurement instrument. Its primary contribution lies in providing a structured analytical lens for examining transdisciplinary collaboration and knowledge creation rather than producing objective quantitative certainty.

These limitations do not undermine the findings; rather, they define the boundaries within which claims arising from this research should be interpreted.

7.4.3 Threats to Validity

Within Action Research, researcher neutrality is not assumed as an achievable goal. Rather, the researcher is recognised as an active participant within the system being studied, where understanding emerges through cycles of intervention, observation, reflection, and refinement. Consequently, the purpose is not to eliminate all sources of bias, but to make assumptions explicit and systematically account for their influence.

Several potential threats to validity may have influenced this research. Selection bias may be present, as participants were drawn from specific educational settings involving multidisciplinary and STEAM-oriented design contexts, potentially attracting students already predisposed toward collaborative and exploratory learning practices. Institutional context bias may also influence the findings, as the research was conducted within a supportive environment that included interdisciplinary teaching partnerships, makerspace access, critique structures, and sustained facilitation. Consequently, some observed outcomes may partly reflect characteristics of the local environment.

The researcher-practitioner role represents an additional potential threat. The researcher simultaneously acted as educator, facilitator, and investigator, enabling close observation of evolving team dynamics and iterative refinement of interventions. While this proximity provided rich contextual understanding, it may also have influenced facilitation practices and interpretation of results. Related cognitive influences may include researcher confirmation and expectancy effects, whereby observations supporting the emerging TD-SDT framework could unintentionally receive greater interpretive emphasis. Given the iterative nature of longitudinal inquiry, earlier observations may also shape later interpretations and framework development.

Self-report bias may also affect participant-generated data, including reflective journals and interviews, where students may consciously or unconsciously frame experiences in socially desirable ways. The TD Process Assessment Framework additionally incorporates qualitative interpretation within its structured scoring approach, introducing potential subjectivity in assessment decisions.

To mitigate these threats, several strategies were employed throughout the study. Longitudinal analysis across seven Action Research cycles reduced reliance on isolated observations. Multiple forms of data triangulation were applied through reflective journals, interviews, reports, artefacts, and researcher observation notes. Reflexive journaling and critical incident analysis were used to identify assumptions and challenge emerging interpretations. The TD-SDT itself evolved iteratively in response to observations rather than being imposed as a fixed explanatory framework. Although these measures cannot eliminate all threats to validity, they increase the transparency, credibility, and confirmability of the findings.

7.4.4 Transferability

This research was conducted within a specific institutional environment that benefited from supportive transdisciplinary conditions, including interdisciplinary teaching collaboration, access to makerspaces, arts integration, critique structures, public exhibition opportunities, and sustained facilitation over multiple years. Consequently, the findings should not be interpreted as demonstrating universal transferability of the precise TD-SDT implementation across all educational or professional contexts.

However, Action Research seeks analytical rather than statistical generalisation. The intent is not to claim that identical outcomes would emerge across all contexts, but rather to provide sufficiently detailed descriptions of processes and mechanisms that enable readers to assess relevance to their own settings.

The TD-SDT does not prescribe specific disciplinary content or institutional configurations. Instead, it identifies broader relational conditions, epistemic mechanisms, and pedagogical practices that support epistemic crossing and collaborative knowledge creation. These elements may therefore be adapted to different educational environments, disciplinary combinations, and organisational contexts.

Furthermore, many of the mechanisms identified within this research—including epistemic mediators such as boundary objects, abstraction, narrative reframing, and epistemic reflexivity—extend beyond STEAM design education and may be applicable within a broader range of collaborative contexts addressing complex societal challenges.

Despite these limitations and potential threats to validity, this study contributes a theoretically informed and empirically grounded understanding of how transdisciplinary collaboration and knowledge creation can be intentionally cultivated. Through sustained longitudinal inquiry, multiple forms of triangulation, and iterative refinement across seven Action Research cycles, the research provides both a conceptual explanation and a practical framework for supporting transdisciplinary STEAM collaboration.

7.5 Future Research

The limitations identified in this study suggest several directions for future research. While the Transdisciplinary STEAM Design Toolkit (TD-SDT) and the TD Process Assessment Framework demonstrated strong potential within the educational environments examined in this dissertation, additional investigation is required to extend, refine, and validate these contributions across broader contexts.

One important direction involves cross-institutional replication**.** The courses analysed in this research were implemented within a single institutional environment. Future studies could examine how the TD-SDT performs across different universities, disciplinary configurations, and cultural contexts to determine whether the epistemic, relational, and pedagogical conditions identified in this research remain robust across alternative settings and disciplinary communities.

Another direction concerns the application of epistemic crossing mechanisms within professional environments**.** Future studies could investigate how the epistemic mechanisms identified in this research operate within professional design, engineering, policy, and innovation environments. Examining how these mechanisms operate in real-world environments would provide insight into how epistemic crossing unfolds in practice.

Longitudinal research may also examine the lasting effects of transdisciplinary STEAM education on professional identity formation**.** Although this study documented how students engaged in epistemic reflexivity, disciplinary negotiation, and collaborative knowledge creation during course participation, the longer-term influence of these experiences remains unknown. Following graduates over time could provide insight into how sustained exposure to epistemic crossing shapes approaches to complex problems and interdisciplinary collaboration.

Further work is also needed to refine and validate the TD Process Assessment Framework. While the framework provides a structured method for examining collaboration and integration, its assessment process remains partly qualitative. Larger-scale studies could strengthen reliability across contexts and support the development of simplified self-assessment instruments aligned with the framework to enable ongoing evaluation of collaborative quality, integration depth, and societal impact.

Technological mediation represents another important avenue of investigation. In later iterations of this research, generative AI emerged as a potential epistemic mediator. Future studies could examine how AI tools influence collaborative ideation*,* conceptual exploration and the ethical dimensions of transdisciplinary knowledge creation.

Another promising direction concerns the role of artistic practices as epistemic and ontological agents within transdisciplinary collaboration**.** The findings of this dissertation suggest that the arts contribute more than creative expression within STEAM contexts. Future work may further examine how artistic practices shape epistemic dispositions, organisational cultures, and collaborative knowledge creation. Such work may also investigate how artistic artifacts function as symbolic infrastructures capable of shaping public discourse and policy imagination around complex societal challenges.

Additional conceptual work may further elaborate the Epistemic Crossing Systemic Model and the model of epistemic reflexivity proposed in this dissertation. Further investigation could examine how dimensions such as epistemic awareness, humility, empathy, control, and epistemic innovation evolve across educational and professional environments. Similarly, future work may explore how artistic practices—including storytelling, abstraction, critique, and speculative design—shape epistemic dispositions, organisational cultures, and collective knowledge creation.

Taken together, these directions suggest a broader research agenda centred on designed epistemic infrastructures for transdisciplinary collaboration**.** The TD-SDT should therefore be understood not as a finished model, but as the foundation of an evolving research programme exploring how epistemic crossing can be intentionally cultivated across educational, professional, and societal contexts.

7.6 Final Reflection

At a time when complex societal challenges increasingly demand collaboration across disciplinary boundaries, this research demonstrates that transdisciplinary integration cannot be assumed to arise simply by bringing diverse experts together. Rather, it requires carefully designed environments that support epistemic crossing, reflexive inquiry, and conceptual exploration.

The findings indicate that artistic practices supported the conditions through which disciplinary knowledge interacted, evolved, and became integrated within collaborative environments. Within the TD-SDT, these practices functioned as epistemic infrastructure supporting epistemic crossing and collaborative knowledge creation.

By articulating these mechanisms and conditions, this research contributes both conceptual insight and practical guidance for educators, researchers, and institutions seeking to cultivate transdisciplinary approaches to the complex challenges of the twenty-first century.

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APPENDIX A Certificate of Ethics Approval

23/05/2024

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

CERTIFICAT D'APPROBATION ÉTHIQUE | CERTIFICATE OF ETHICS APPROVAL

Numéro du dossier / Ethics File Number	H-10-23-9046
Titre du projet / Project Title	Looking for evidence of positive impacts of new pedagogic approaches and tools on team's success in class.
Type de projet / Project Type	Thèse de doctorat / Doctoral thesis
Statut du projet / Project Status	Approuvé / Approved
Date d'approbation (jj/mm/aaaa) / Approval Date (dd/mm/yyyy)	23/05/2024
Date d'expiration (jj/mm/aaaa) / Expiry Date (dd/mm/yyyy)	22/05/2025

Équipe de recherche / Research Team

Chercheur / Researcher	Affiliation	Role
Chantal RODIER	École de conception et d'innovation pédagogique en génie / School of Engineering Design and Teaching Innovation	Chercheur Principal / Principal Investigator
Liam PEYTON	École de conception et d'innovation pédagogique en génie / School of Engineering Design and Teaching Innovation	Superviseur / Supervisor
Jason MILLAR	École de science informatique et de génie électrique / School of Electrical Engineering and Computer Science	Co-superviseur / Co-supervisor

Conditions spéciales ou commentaires / Special conditions or comments

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23/05/2024

Université d'Ottawa

Bureau d'éthique et d'intégrité de la recherche

University of Ottawa

Office of Research Ethics and Integrity

Le Comité d'éthique de la recherche (CÉR) de l'Université d'Ottawa, opérant conformément à l'*Énoncé de politique des Trois conseils* (2014) et toutes autres lois et tous règlements applicables, a examiné et approuvé la demande d'éthique du projet de recherche ci-nommé.

L'approbation est valide pour la durée indiquée plus haut et est sujette aux conditions énumérées dans la section intitulée "Conditions Spéciales ou Commentaires". Le formulaire « Renouvellement ou Fermeture de Projet » doit être complété quatre semaines avant la date d'échéance indiquée ci-haut afin de demander un renouvellement de cette approbation éthique ou afin de fermer le dossier.

Toutes modifications apportées au projet doivent être approuvées par le CÉR avant leur mise en place, sauf si le participant doit être retiré en raison d'un danger immédiat ou s'il s'agit d'un changement ayant trait à des éléments administratifs ou logistiques du projet. Les chercheurs doivent aviser le CÉR dans les plus brefs délais de tout changement pouvant augmenter le niveau de risque aux participants ou pouvant affecter considérablement le déroulement du projet, rapporter tout évènement imprévu ou indésirable et soumettre toute nouvelle information pouvant nuire à la conduite du projet ou à la sécurité des participants.

The University of Ottawa Research Ethics Board, which operates in accordance with the *Tri-Council Policy Statement* (2014) and other applicable laws and regulations, has examined and approved the ethics application for the above-named research project.

Ethics approval is valid for the period indicated above and is subject to the conditions listed in the section entitled "Special Conditions or Comments". The "Renewal/Project Closure" form must be completedfour weeks before the above-referenced expiry date to request a renewal of this ethics approval or closure of the file.

Any changes made to the project must be approved by the REB before being implemented, except when necessary to remove participants from immediate endangerment or when the modification(s) only pertain to administrative or logistical components of the project. Investigators must also promptly alert the REB of any changes that increase the risk to participant(s), any changes that considerably affect the conduct of the project, all unanticipated and harmful events that occur, and new information that may negatively affect the conduct of the project or the safety of the participant(s).

Germain ZONGO
Responsable d'éthique en recherche / Protocol Officer
Pour/For **Daniel LAGAREC** Président(e) du/ Chair of the **Comité d'éthique de la recherche en sciences de la santé et sciences / Health Sciences and Sciences Research Ethics Board**

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APPENDIX B Publications and Scholarly Outputs Arising from This Research

Portions of this research have been disseminated through peer-reviewed publications and conference presentations during the doctoral project. These publications contributed to the development and refinement of the Transdisciplinary STEAM Design Toolkit and the TD Process Assessment Framework.

Active research		2
Papers in refereed conference proceedings		8
Dissemination: in media		5
Papers read, keynotes, presentations		14
Research-creation art installations/exhibits		12
Others		37
STEAM Symposium Organisation	1	
Workshops presented	5	
Courses taught	29	
Internship mentorship/supervision	2	

Active Research:

1. Rodier, C. (2018 - 2026) PhD Research-- **Transdisciplinary STEAM Design Toolkit: Leveraging the Benefits of Artistic Approaches in Multidisciplinary Collaborations**
2. Millar, J. et al., (2025 - 2030) SSHRC Insight Grant Developing a Targeted Transdisciplinary Framework and Toolkit that Integrate Ethics, Law, Policy,

Papers in Refereed Conference Proceedings:

3. **Rodier, C.**, Newland, F., (2026). Beyond Early Convergence: A Transdisciplinary STEAM Approach to Expanding Creativity in Engineering Education. Proceedings of the Canadian Engineering Education Association (CEEA).
4. **Rodier, C.**, Bruce, D, (2026). Existential Proximity: How Students Can Gain Connection to their Learning from Observing LLMAI Operation. Proceedings of the Canadian Engineering Education Association (CEEA).
5. **Rodier, C.**, Carter, C. (2023). "STEAM Transdisciplinarity Model Critique", 2023 IEEE IFEES World Engineering Education Forum-Global Engineering Deans Council (WEEF-GEDC)
6. **Rodier, C.**, Millar, J., Deisinger, W., Hodgson, S.J. (2023). Examining AI through the Lens of Art and STEAM, 2023 IEEE IFEES World Engineering Education Forum-Global Engineering Deans Council (WEEF-GEDC)
7. Zacharias, K., Seniuk Cicek, J., Wilkinson, L., **Rodier, C.**, Patterson, L., Bezerra Rodrigues, R., Tallman, K. (2023). "Transdisciplinary Approaches in Canadian Engineering Education", 25th Annual Colloquium on International Engineering Education (ASEE)
8. Patterson, L., **Rodier, C.**, Bezerra Rodrigues, R., Seniuk Cicek, J., Tallman, K., Wilkinson,

L., Zacharias, K. (2022). "Cross-Institutional Reflections on Engineering and Humanities in Canada", 25th Annual Colloquium on International Engineering Education (ACIEE)

9. **Rodier, C.**, Galaleldin, M., Boudreau, J., Anis, H., & Peyton, L. (2021). STEAM–Arts Integration Frameworks for Transdisciplinarity. Proceedings of the Canadian Engineering Education Association (CEEA).
10. **Rodier, C.**, Galaleldin, M., Boudreau, J., & Anis, H. (2019). From stem to steam in engineering design. Proceedings of the Canadian Engineering Education Association (CEEA).

Dissemination: Interviews and Media Engagement

1. Samuel, S. (August 29, 2023). "Drawing a line." THIS Magazine. Paper & Online: https://this.org/2023/08/29/drawing-a-line/
2. Taylor, K. (March 24, 2023). "*As AI debate swirls, artists are torn between embracing it and trying to break it.*" The Globe and Mail, Arts & Books. Paper & Online: https://www.theglobeandmail.com/arts/art-and-architecture/article-as-ai-debate-swirls-artists-are-torn-between-embracing-it-and-trying/
3. Rodier, C. (2022). "Art to Critically Examine AI & Robotics". The Ingenium Channel, https://ingeniumcanada.org/channel/articles/art-to-critically-examine-ai-robotics
4. Beauvais, J. (May 2019) Make the Future Podcast Episode10
5. Beauvais, J. (Feb 2019) Make the Future Podcast Episode 4

Papers Read:

Invited Keynotes

1. **Rodier, C.** (2024). "STEAM Research at the University of Ottawa", Art in Silico, Michigan Technological University, Houghton, Michigan, USA
2. **Rodier, C.** (2022). "Driving Change in Engineering: Using a STEAM based approach to facilitate a workforce of the future for Engineering.", International STEAM Conference, STEAM House, Birmingham City University, Birmingham, UK

Invited Academic Symposium, Conference Panel Presentations

1. **Rodier, C.**, Stec, R. (2024). Panelist "Generative AI breaking artistic and programming barriers", Art in Silico, Michigan Technological University, Houghton, Michigan, USA
2. **Rodier, C.**, Millar, J. (2023). ""Examining AI through the Lens of Art and STEAM."", International STEAM Conference, STEAM House, Birmingham City University, Birmingham, UK
3. **Rodier, C.**, Millar, J. (2023). Panelist. "Machine Mayhem: A.I. and its Impact on the Creative Process" Sci-Art Symposium. SAW Gallery and Embassies of Republic of Slovenia and Embassies of Republic of Germany (OAG 2023). Ottawa, Canada.
4. **Rodier, C**. & Millar, J. (2023). "STEAM in the CRAiEDL Collective, The Ethics and Art of AI", AI + Society International Speaker series, Ottawa, Canada
5. **Rodier, C.** (2022). Panelist. "Intersections/driving impact/transformational change", International STEAM Conference, STEAM House, Birmingham City University, Birmingham, UK

6. **Rodier, C.**, Millar, J. (2022). Featured speakers on Art & AI – talk-back, *"*The Anniversary: A Play", Ottawa Art Gallery, Produced by Institute for Science, Society & Policy (ISSP). Playwright Jacob Berkowitz and director Kevin Orr, and ISSP Director Monica Gattinger.
7. **Rodier, C.** (2019). Panelist. « Innovations dans le monde de l'art », 32e Entretiens Jacques-Cartier, University of Ottawa

Presentations:

1. Zacharias, K., Seniuk Cicek, J., Wilkinson, L., **Rodier, C.**, Patterson, L., Bezerra Rodrigues, R., Tallman, K. (2023). "Transdisciplinary Approaches in Canadian Engineering Education", 25th Annual Colloquium on International Engineering Education (ASEE)
2. Patterson, L., **Rodier, C.**, Bezerra Rodrigues, R., Seniuk Cicek, J., Tallman, K., Wilkinson, L., Zacharias, K. (2022). "Cross-Institutional Reflections on Engineering and Humanities in Canada", 25th Annual Colloquium on International Engineering Education (ACIEE)
3. **Rodier, C.**, Galaleldin, M., Boudreau, J., Anis, H., & Peyton, L. (2021). STEAM–Arts Integration Frameworks for Transdisciplinarity. *Proceedings of the Canadian Engineering Education Association*.
4. **Rodier, C.**, Galaleldin, M., Boudreau, J., & Anis, H. (2019). From stem to steam in engineering design. *Proceedings of the Canadian Engineering Education Association (CEEA)*.
5. **Rodier, C.** (2019) 'À l'épreuve des robots – Robot Proof', Tournée Numérique, Digital Tour, Conference Series, Quebec, Ontario

Research-Creation Art Installations (Artifacts / exhibits):

1. Deisinger, W. Hodgson, S. J., Millar, J. **Rodier, C.** (2022). "CRAiEDL Project: **I'm Honoured to Serve**." [Visual Artwork]. ***Ingenium – Kanata North uOttawa Campus***. Exhibited at the University of Ottawa's Kanata North Campus in Kanata June-Aug 2022. Fig. 1 I'm Honoured to Serve – installation, A.Gordon photo A.Gordon.
2. Deisinger, W. Hodgson, S. J., Millar, J**. Rodier, C**. (2022). "CRAiEDL Project: **I'm Honoured to Serve.**" [Visual Artwork]. ***Art Engine.*** Exhibited at Art Engine in the Artscourt Location, Ottawa, Canada, June-Aug 2022.

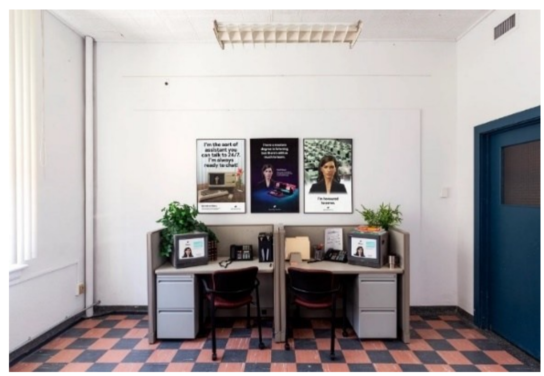


Fig. 1 I'm Honoured to Serve – installation, A.Gordon

3. Deisinger, W., Hodgson, S. J., Millar, J., **Rodier, C.** (2022). "CRAiEDL Project: **I'm Honoured to Serve.**" [Visual Artwork]. ***CRAiEDL Pop-up Exhibition***. Exhibited at **University of Ottawa's auxiliary visual arts building,** 200 Wilbrod Street Rm114, in Ottawa on May 19th,2022.
4. Deisinger, W., Hodgson, S J., Millar, J., **Rodier, C.** (2022). "**Calibrating Stretched Transparency.**" [Visual Artwork]. Video exhibited at the **University of Ottawa's Kanata North Campus** in Kanata April-May 2022. (Fig. 2)

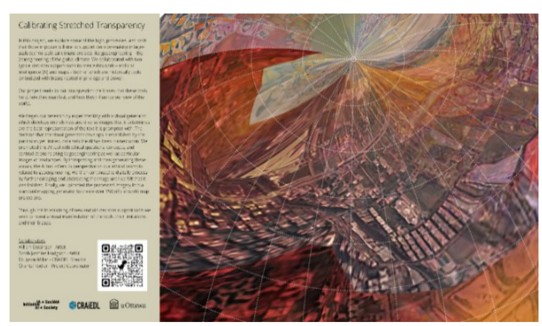


Fig. 2 Calibrating Stretched Transparency: Web App.

5. Deisinger, W., Hodgson, S. J., Millar, J., **Rodier, C.** (2022). "CRAiEDL Project: **Calibrating Stretched Transparency**." ***Arts Matters Conference*** [Digital Video]. Online: https://www.unb.ca/fredericton/arts/arts-matters-conference/artwork.html. Exhibited at GatherTown Virtual Gallery and The Provincial Archives in Fredericton April 1st-3rd, University of New Brunswick, Fredericton, Canada.

6. Hodgson, SJ., Deisinger, W., Millar, J., **Rodier, C.** (2021). **"Calibrating Stretched Transparency."** [Visual Artwork]. **Online: https://craiedl.ca/calibrating-stretched-transparency/**

7. Hodgson, SJ., Deisinger, W., Millar, J, **Rodier, C.** (2022). **"I'm Honoured to Serve."** [Visual Artwork]. **Online: https://craiedl.ca/im-honoured-to-serve/**

8. Hodgson, SJ., Deisinger, W., Millar, J, **Rodier, C.** (2022). **"I'm Honoured to Serve." & "Calibrating Stretched Transparency.", in "Art to Critically Examine AI & Robotics"** [Visual Artwork]. **The Ingenium Channel**, Online: https://ingeniumcanada.org/channel/articles/art-to-critically-examine-ai-robotics

Fig. 3 CRÉATICITÉ Digital Art Installation, C. Rodier

9. Charbonneau, S., Kanyoka, R., Mehour, S., **Rodier, C.** (2020-21). **"CRÉATICITÉ: Mur de la créativité"**, [Visual Artwork – Interactive installation]. **Collège La Cité**, Ottawa, Canada. (Fig. 3)

10. **Rodier, C.** (2019). Tournée Numérique - **Digital Art Exhibit**, Digital Tour Conference Series, **Art Engine** Gallery, Ottawa, Canada.

11. Carrière,E., Lacaille, H., Lebedev, E., LeBlanc, M., Anis, H., **Rodier, C.** .**"Equilibrium"**, [Visual Artwork – Interactive installation]. **STEM Building, University of Ottawa**, Ottawa, Canada. (Fig. 4)

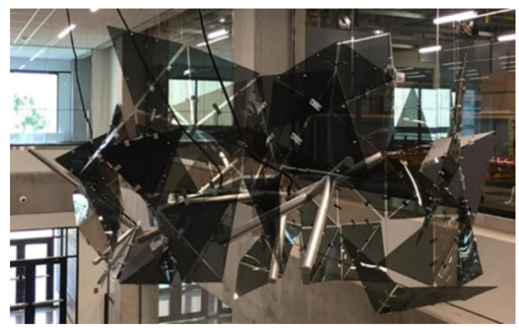


Fig. 4 EQUILIBRIUM (Video) photo: B.Findley

12. Deeljur, K., Hodgson, S., Oulanova, L., Shah, D., Hassan, M., Sanaknaki, A., Sarmad, N., M., Weller, L., Anis, H., **Rodier, C.** (2018). "**Surface Tension**", [Visual Artwork – Interactive installation]. **STEM Building, University of Ottawa,** Ottawa, Canada. (Fig. 5)

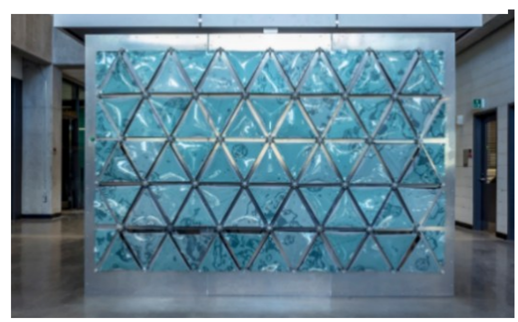


Fig. 5 SURFACE TENSION (Video) photo: S.Hodgson

Others (Symposium, Workshops, Op-Eds, Articles):

Symposium Organised:

Rodier, C, Kharouba, H, Hegel, A. .*(2025) Crossing Boundaries Symposium : Mobilizing STEAM to Tackle Climate Change, May 3-4 uOttawa, www.boundaryxr.ca*

Workshop Presented:

1. Millar, J., **Rodier, C.** (2023) Metaphors in AI & STEAM, International AI + Society Conference, University of Ottawa, Ottawa, Canada (Oct)

2. Zacharias, K., Wilkinson, L., Maciag, T., **Rodier, C.**, Tallman, K., Seniuk Cicek, J., Patterson, L., Bezerra Rodrigues, R. (2023), "Got enough on your plate? Finding space and time for meaningful sociotechnical instruction", (Workshop), CEEA Conference, UBC Okanagan and Okanagan College, Kelowna, BC, Canada (June)

3. Patterson, L., **Rodier, C.**, Bezerra Rodrigues, R., Seniuk Cicek, J., Tallman, K., Wilkinson, L., Zacharias, K. (2022), "Leveraging Interdisciplinarity: A workshop for Engineering Educators.", (Workshop), CEEA Conference, York University, Toronto, Canada (June)
4. Patterson, L., **Rodier, C.**, Bezerra Rodrigues, R., Seniuk Cicek, J., Tallman, K., Wilkinson, L., Zacharias, K. (2022), "Collaboratorium on Transdisciplinary Approaches to Support Technological Stewardship", (Workshop), CEEA Conference, York University, Toronto, Canada (June)
5. Anis, H., **Rodier, C.**, Boudreau, J. (2019), "Including the Arts in Engineering Education", (Workshop), CEEA Conference, University of Ottawa, Ottawa, Canada (June)

STEAM-related course curriculum development and teaching:

Graduate Courses - University of Ottawa

2026, 25, 23, 22, 20	DTI6304/GNG5300 STEAM Multidisciplinary Design, enrolment 27,24
2025(2), 24, 23, 22, 21, 20	DTI7103 Visual Literacy and UXD Principles, enrolment 27,24

Undergraduate Courses - University of Ottawa

2026,25,23, 22, 21, 20	GNG3100/AHL3100 STEAM Multidisciplinary Design, enrolment 30, 100, 27, 8, 22, 18
2023, 2022, 2021	AHL3700 Créativité et Innovation, enrolment 44,29
2019	GNG1103/ART2926 Engineering Design / Sculpture, enrolment 32
2018	GNG1503 Génie de la conception, enrolment 35

College Courses - Collège La Cité

2021, 2020, 2019	023865 Art interactif dans l'espace public, enrolment 3,6,1
2021, 2020, 2019	023860 Art interactif, enrolment 2,14,11
2021	023874 Installation Publique, enrolment 6

Mentoring & Supervising
Stage Collégiale – La Cité Collégiale

2020 Stage STIAM: Mur de la créativité, enrolment 6

Undergraduate internship courses - University of Ottawa

2018 STEAM Internship: STEAM Creations, enrolment 8+4

APPENDIX C Terms for Collaborations Including Art

Term	Definition	Reference
Art-science/ Sci-art / SciArt	Interdisciplinary collaborations where artistic and scientific methods intersect to create new forms of knowledge, representation, or critique.	(Wilson, 2002)
Art4Science	Artistic initiatives that visualise, support, or communicate scientific research, often through residencies programs (Candy & Edmonds, 2011).	(Candy & Edmonds, 2011)
Hybrid	Creative practices that combine art, science, and technology—often through emerging media, biotechnology, or AI—producing novel forms of expression and insight.	(Lovejoy, 2004)
H-shaped	A metaphor for individuals with deep expertise in two fields and integrative capacity across domains, supporting complex, cross-sector collaboration.	(Guest, 1991)
Art Research / Artistic Research	A methodology in which the production of creative work is integrated into the research process, generating knowledge through making.	(Chapman & Sawchuk, 2012)
Research-Creation	Inquiry driven by artistic practice, where the creative process itself is a mode of investigation and the artwork is a research outcome.	(Hubner, 2024)
SEAD	Acronym for Science, Engineering, Art, and Design—advocating for the integration of arts and design thinking within STEM fields.	(Malina, 2010)
SMET	The National Science Foundation (NSF) first used the term SMET in 2001 which was later re-arrange into STEM.	(Belbase, 2020)
STEM	Science, Technology, Engineering, Mathematics. A curriculum and research focus on science, technology, engineering, and mathematics, emphasising analytic and technical skills.	(National Science Foundation (NSF), 2010)
STEAM *	An extension of STEM that incorporates the arts to foster creativity, critical thinking, and design in scientific and technological contexts. Arts integration is an approach to teaching in which students construct and demonstrate understanding through an art form.	(Yakman, 2008; Liao, 2016)

	Students engage in a creative process which connects an art form and another subject area and meets evolving objectives in both.	
STEMM	Science, Technology, Engineering, Mathematics, Medicine	(Root-Bernstein et al., 2019)
STEAMM	Science, Technology, Engineering, Arts, Mathematics, Medicine.	(Diamond, 2019)
ST2EAM	Science, Technology, Transformative learning, Engineering, Arts, and Mathematics.	(Trott et al., 2020, p. 1079)
STREAM	Science, Technology, Reading, Engineering, Arts, and Mathematics.	(Root-Bernstein et al., 2011)
STREAM	STEAM + Research = STREAM.	(Root-Bernstein et al., 2011)
STREAM-h	Science, Technology, Engineering, Arts, and Mathematics through reading-writing for humanity.	(Belbase, 2020)
STEAMM+D	Science, Technology, Engineering, Arts, Mathematics, Medicine and Design.	(Diamond, 2019)
Third Culture	Term for scientifically literate thinkers who bridge the divide between science and the humanities, shaping public intellectual discourse.	(Brockman, 1995)
Third Space	A conceptual space where disciplinary boundaries blur, allowing hybrid identities, perspectives, and knowledge to emerge.	(Bhabha, 1994)
T-Shaped	A competency model describing individuals with deep expertise in one area and broad knowledge across disciplines to enable collaboration.	(Johnston, 1978)

APPENDIX D Documented STEAM Benefits

The following table presents generic qualities of STEAM as highlighted in the literature consulted for this research.

Overview of qualities associated with STEAM working and thinking	
Qualities / Characteristics	**Sources**
Balance and Navigation	Chappell et al. (2019)
Collaboration, Cooperation, Reciprocity	Bertrand and Namukasa (2020); Chappell et al. (2019); Drozd et al. (2017); Guyotte et al. (2014); Pollock et al. (2017); Segarra et al. (2018)
Communication, Dialogue	Bequette and Bequette (2014); Chappell et al. (2019); Guyotte et al. (2014)
Connecting (people, knowledge, environment, processes), Contextualisation, Bigger Picture	Bequette and Bequette (2014); Burnard et al. (2021); Chappell et al. (2019); Clark and Button (2011); Drozd et al. (2017); Guyotte et al. (2014)
Creativity; Creative Thinking; Synthetic Thinking	Bequette and Bequette (2014); Chappell et al. (2019); Conradty and Bogner (2018); Guyotte et al. (2014, 2015); Catterall, 2017
Critical Thinking/Reasoning; Realising Strengths and Weaknesses	Bertrand and Namukasa (2020); Chappell et al. (2019); Guyotte et al. (2014); Timotheou and Ioannou (2021);
Cultural Sensitivity	De la Garza (2019); Segarra et al. (2018)
Curiosity	Bequette and Bequette (2014); Bertrand and Namukasa (2020)
Empowerment and Agency; Make/Do	Bertrand and Namukasa (2020); Chappell et al. (2019); Guyotte et al. (2014)
Empathy	Guyotte et al. (2014)
Ethics; Trust	Chappell et al. (2019); Guyotte et al. (2014)
Experimentation and Failure; Iterations	Bequette and Bequette (2014); Bertrand and Namukasa (2020)
Holistic	Drozd et al. (2017); Guyotte et al. (2014)
Inclusivity	Bequette and Bequette (2014); Pollock et al. (2017); Segarra et al. (2018)
Imagination	Bequette and Bequette (2014); Bertrand and Namukasa (2020); Chappell et al. (2019)
Immersion and Play	Bertrand and Namukasa (2020); Chappell et al. (2019); Drozd et al. (2017)
Innovation, Advancing knowledge/methods	Bertrand and Namukasa (2020); Kim et al. (2018)
Interdisciplinary; Transdisciplinary	Bertrand and Namukasa (2020); Chappell et al. (2019); Drozd et al. (2017); Guyotte et al. (2014); Pollock et al. (2017)
Meaning making	Guyotte et al. (2014); Segarra et al. (2018)
Problem-based (problem-finding, -framing, -solving); Authentic	Bequette and Bequette (2014); Bertrand and Namukasa (2020); Clark and Button (2011); Drozd et al. (2017); Guyotte et al. (2014); Kim et al. (2018); Segarra et al. (2018)
Process-orientated	Bequette and Bequette (2014); Bertrand and Namukasa (2020); Chappell et al. (2019); Guyotte et al. (2014)
Project-based; Partnership	Drozd et al. (2017); Guyotte et al. (2014)
Reflection	Bertrand and Namukasa (2020); Guyotte et al. (2014); Segarra et al. (2018)
Risk-taking	Bequette and Bequette (2014); Chappell et al. (2019)
Shared language; Common language	Guyotte et al. (2014); Van Gansbeke and Groenewould (2020)
Tolerate ambiguity; Lack of specificity	Bequette and Bequette (2014)
Leads to innovation, Strengthen the economy	Catterrall, 2017; De Fay, 2005; Girão et al., 2018
Make STEM more attractive	(E.g., Billiar et al., 2014; Catterall, 2017; Drozd et al., 2017; Segarra et al., 2018)

Augmented version of table found in (Carter et al., 2021)

Similarities and Differences between Science and Art

How are science and art similar? How are they different? This analysis is useful for understanding the prospects for future relationships.

Differences between Art and Science	
Art	Science
Seeks aesthetic response	Seeks knowledge and understanding
Emotion and intuition	Reason
Idiosyncratic	Normative
Visual or sonic communication	Narrative text communication
Evocative	Explanatory
Values break with tradition	Values systematic building on tradition and adherence to standards

Similarities between Art and Science

Both value the careful observation of their environments to gather information through the senses.
Both value creativity.
Both propose to introduce change, innovation, or improvement over what exists.
Both use abstract models to understand the world.
Both aspire to create works that have universal relevance.

(S. Wilson, 2002)

APPENDIX E STEAM Taxonomy from Literature

A taxonomy focuses on concepts and the relationship between concepts. I have reviewed the literature to terms, concepts, used and not used in STEAM literature to date.

Term	Meaning	References
Framework	A framework is a large conceptual structure that offers direction, guidance, and a common language for tackling a task or a problem. It is a system of rules, precepts, or presumptions that aids in the organisation and comprehension of complicated material. A framework can be modified to fit multiple contexts or scenarios and is frequently used to provide a high-level picture of an issue or situation.	(Daily Agile, 2017)
STEAM	STEAM is an educational approach to learning that uses Science, Technology, Engineering, the Arts and Mathematics as access points for guiding student inquiry, dialogue, and critical thinking. The end results are students who take thoughtful risks, engage in experiential learning, persist in problem-solving, embrace collaboration, and work through the creative process.	(Henriksen, 2014)
	Science & Technology interpreted through Engineering& the Arts; all understood with elements of Mathematics.	(Yakman, 2010)
STEAM Definition (7 core principles)	our discussions illustrated the importance of the combination of qualities and attention to the underlying paradigm(s) as key. By employing these characteristics together, STEAM creates a (mental, physical, creative) space that adds value, new perspectives and fresh thinking. Our agreed STEAM definition adopted the following format. "A Higher Education approach to STEAM (potentially) involves a culture (or cultures) that puts the Arts and Sciences on an equal footing; operating within a paradigm that is process-driven, student-centred, 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 emphasise 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."	(Carter et al., 2021, p. 21)
STEAM Approach Or Process or Project	In general, STEAM approach can be considered the wider expression, covering strategies, programmes, fields, and philosophies.	(Burns et al., 2021, p. 4)
STEAM Method	STEAM method more clearly relates to specific techniques. Therefore, this handbook's perspective is that STEAM methods sit within STEAM approaches.	(Burns et al., 2021, p. 6)
Typology of STEAM approaches	Behaviour, Cultures, Engagement and Spaces.	(Burns et al., 2021, p. 12)
STEAM Methodologies	STEAM methods for implementation across the diverse HE contexts.	(Carter et al., 2021, p. 5)

	The focus is on developing a comprehensive methodological framework to support the integration of STEAM thinking in curriculum design through, for example, speculative design, art thinking, process-based research and participatory practice.	
STEAM Competencies (8)	Collaboration Communication Exploration Critical thinking Civic and social skills Sustainability Metacognition Wellbeing	(Carter et al., 2021, p. 13)
STEAM Competencies self-assessment tool	Open question prompts and survey questions to assess each competency based on their characteristics and indicators	(Ussher et al., 2023)
STEAM Meta-level evaluation for the project as a whole	to assess the partnership, the modes of collaboration and the resulting outcomes – utilising the STEAM definitions and competences generated within the project.	(Carter et al., 2021, p. 5)

APPENDIX F TD Process Assessment Framework

TD Process Assessment Framework			
TD Process Quality – TD Collaboration			**TPQ Score**
	Collaborative Process	C1- Trust	L/M/H [0,3]
		C2- Communication	
		C3- Mutual Learning	
		C4- Conflict Handling (Friction)	
		C5- Shared Problem Framing	
	Reflexivity	C6- Equal footing, Power relationships & fairness	
		C7- Team Critical Self-Awareness	
TD Integration Quality – TD Knowledge Creation (Tangible)			**TIQ Score**
	Artifacts Created	K1- Epistemic (Disciplinary) Grounding	L/M/H [0,3]
		K2- Integration Depth & Coherence	
		K3- Advancement of Understanding (novelty)	
TD Societal Effects – TD Knowledge Creation (Intangible)			**TSE Score**
	Learning & Capacity Building of Participants	K4- Cognitive, social & practical competencies	L/M/H [0,3]
	Societal Usefulness	K5- Salient, credible, legitimate, actionable	
	Societal Impacts	K6- Policy & Practices Change	
TD Process Score [0,9] where: Low =[0,2]; Medium=[3,5]; High=[6,9]			**TD Process Score**

APPENDIX G Codebook for Thematic Analysis

TD Codebook for Collaboration, Integration, and Societal Effects

This codebook operationalises TD collaboration, integration, and societal effects by distinguishing process quality (C-codes) from tangible and intangible knowledge creation outcomes in integration quality and societal effects (K-codes), enabling a relational assessment of how collaborative dynamics shape TD knowledge production.

Coding Notes (for Methodological Transparency):

- Unit of analysis: Team (per iteration), with excerpts coded at the individual level
- Units of Observation (Primary sources): Reflective journals, interviews, team reports, prototypes, final artifacts
- Interpretive principle:
    - Collaboration codes (C1–C7) capture process quality
    - Knowledge codes (K1–K6) capture integration quality and societal effects

  Important: TD Knowledge Creation (K-codes) must be interpreted in relation to the TD Collaboration processes (C-codes) that generated them.

Method:

To perform the TD assessment of the TD Collaboration and TD knowledge Creation experienced by each team within an iteration, we performed a deductive analysis using this codebook per team on all students' reflections and team reports using quotes (keeping the references).

TD Codebook

Cluster A — TD Process Quality: TD Collaboration

Code	Dimension	Definition	Key Indicators	Typical Evidence
C1	Trust	The extent to which team members demonstrate mutual confidence, psychological safety, and reliability.	Open sharing of ideas; willingness to take risks; reliance on others' expertise	Reflective journals; meeting notes; design decisions showing shared ownership
C2	Communication	Quality and effectiveness of information exchange across disciplines.	Clear explanations; translation of disciplinary language; active listening	Journals; interviews; peer feedback
C3	Mutual Learning	Evidence that team members learn from each other across disciplinary boundaries.	Acknowledging learning from others; adopting unfamiliar approaches	Journals; interviews; evolving design rationale
C4	Conflict Handling (Friction)	Ability to engage constructively with disagreement, tension, or epistemic differences.	Naming disagreements; negotiating trade-offs; transforming conflict into ideas	Journals; interviews; documented design pivots
C5	Shared Problem Framing	Collective development or reframing of the problem from multiple perspectives.	Joint definition of goals; expansion of problem scope; integration of concerns	Early reports; concept maps; journals
C6	Equal Footing, Power & Fairness	Degree to which disciplinary voices are valued equitably and power is negotiated fairly.	Balanced participation; recognition of diverse expertise; shared decision-making	Journals; interviews; team contracts
C7	Team Critical Self-Awareness	Reflexive awareness of team dynamics, limitations, and collaboration quality.	Self-critique; recognition of bias or imbalance; process reflection	Reflective journals; final reports

Cluster B — TD Integration Quality: TD Knowledge Creation (Tangible)

Code	Dimension	Definition	Key Indicators	Typical Evidence
K1	Epistemic (Disciplinary) Grounding	Accuracy and appropriateness of disciplinary knowledge used in the project.	Correct use of methods; justified decisions; awareness of constraints	Reports; prototypes; technical documentation
K2	Integration Depth & Coherence	Degree to which disciplinary perspectives are meaningfully integrated rather than juxtaposed.	Hybrid frameworks; coherent synthesis; cross-referencing inputs	Prototypes; final artifacts; design rationale
K3	Advancement of Understanding (Novelty)	Extent to which integration produces new insights, approaches, or solutions.	Original concepts; unexpected combinations; peer/client recognition	Final artifacts; presentations; feedback

Cluster C — TD Societal Effects: TD Knowledge Creation (Intangible)

Code	Dimension	Definition	Key Indicators	Typical Evidence
K4	Learning & Capacity Building	Development of participants' cognitive, social, and practical TD competencies.	Increased reflexivity; collaboration skills; confidence in TD work	Journals; interviews; self-assessments
K5	Societal Usefulness	Degree to which outputs are relevant, credible, legitimate, and actionable.	Stakeholder relevance; usability; contextual fit	Client feedback; evaluations; adoption intent
K6	Societal Impacts	Evidence of influence on practices, decisions, or policies beyond the course.	Implementation; behaviour change; institutional uptake	Partner reports; follow-up documentation

APPENDIX H Rubric - TD Process Quality

Examine the extracted evidence (student quotes found using deductive thematic analysis) to fill out the TD Process Quality rubric for each team.

TD Process Quality Assessment Rubric			
C1 — Trust			
Score	**Level**	**Descriptor**	**Indicators (Observed Evidence)**
0	Absent	Lack of trust inhibits collaboration	Defensive behaviour; reluctance to share ideas or uncertainty
1	Emerging	Conditional or uneven trust	Participation varies by role, discipline, or confidence
2	Developing	Stable trust supports collaboration	Open discussion; respectful feedback and critique
3	Established	High trust enables risk-taking	Willingness to share unfinished ideas and admit uncertainty

C2 — Communication

Score	Level	Descriptor	Indicators (Observed Evidence)
0	Absent	Communication breakdowns	Misunderstandings; parallel work without alignment
1	Emerging	Basic information exchange	Updates shared but meanings remain siloed
2	Developing	Dialogic communication	Active listening; clarification across disciplines
3	Established	Integrative communication	Shared language enabling collective sense-making

C3 — Mutual Learning

Score	Level	Descriptor	Indicators (Observed Evidence)
0	Absent	No evidence of learning across roles	Knowledge remains discipline-bound
1	Emerging	Occasional learning moments	Ad hoc explanations without reciprocity
2	Developing	Active knowledge exchange	Skill sharing; peer teaching within the team
3	Established	Sustained mutual learning	Collective capability grows over time

C4 — Conflict Handling (Friction)

Score	Level	Descriptor	Indicators (Observed Evidence)
0	Absent	Conflict undermines collaboration	Avoidance, escalation, or unresolved tension
1	Emerging	Conflict acknowledged but unmanaged	Disagreements noted without productive resolution
2	Developing	Conflict contributes to refinement	Negotiated decisions; learning through disagreement
3	Generative	Conflict drives insight	Friction leads to reframing or conceptual breakthroughs

C5 — Shared Problem Framing

Score	Level	Descriptor	Indicators (Observed Evidence)
0	Absent	No shared understanding of the problem	Competing or incompatible problem definitions
1	Emerging	Partial alignment on goals	Agreement on tasks but not on meaning
2	Developing	Shared framing guides work	Co-created problem statements inform decisions
3	Established	Dynamic, reflexive framing	Problem definition evolves through collective inquiry

C6 — Equal Footing, Power Relationships & Fairness

Score	Level	Descriptor	Indicators (Observed Evidence)
0	Absent	Power asymmetries dominate	Certain voices consistently marginalised
1	Emerging	Awareness of imbalance	Attempts to include others without structural change
2	Developing	Relative equity in participation	Turn-taking; role negotiation; shared influence
3	Established	Equitable collaboration	Authority distributed by expertise and context

C7 — Team Critical Self-Awareness

Score	Level	Descriptor	Indicators (Observed Evidence)
0	Absent	No collective reflection	Problems externalised; no process critique
1	Emerging	Episodic reflection	Issues noted but not acted upon
2	Developing	Reflective adjustments	Team adapts practices based on reflection
3	Established	Ongoing critical self-awareness	Continuous monitoring and recalibration of team processes

Each dimension is assessed at the team level using convergent qualitative and material evidence generated across multiple units of observation. Scores reflect the strength and quality of emergent TD processes rather than the causal impact of specific tools or activities.

APPENDIX IRubric - K1 - Disciplinary Grounding

Rubric - K1 - Disciplinary Grounding (apply for each discipline involved)			
Score [0–3]	**Level**	**Descriptor**	**Indicators**
0 - No Discipline Grounding	Absent or Incorrect Disciplinary Grounding	Disciplinary knowledge is missing, misunderstood, or misapplied. (Artifact failed basic disciplinary expectations)	•Little or no use of relevant disciplinary concepts or methods •Design decisions lack disciplinary relevance •Artifact reveals conceptual or technical errors.
1 – Low	Surface or Procedural Disciplinary Grounding	Disciplinary knowledge is present but applied superficially or mechanically. (Artifact “works” but lacks conceptual grounding)	•Basic disciplinary concepts are referenced but not explained •Methods are followed by rote (templates, formulas, tools) •Disciplinary contributions remain isolated or additive •Limited awareness of disciplinary assumptions or constraints.
2 – Medium	Functional and Appropriate Disciplinary Grounding	Disciplinary knowledge is applied correctly and purposefully to support the project. (Artifact meets disciplinary expectations)	•Appropriate disciplinary methods and concepts are used accurately •Design decisions are justified using disciplinary reasoning •Clear articulation of each discipline’s role in the project •Awareness of disciplinary constraints, standards, or limitations
3 – High	Reflexive and Generative Disciplinary Grounding	Disciplinary expertise is used critically, reflexively, and as a resource for integration. (Artifacts demonstrates creative yet grounded use of disciplinary knowledge)	•Team members articulated strengths and limits of their discipline •Disciplinary assumptions are questioned or adapted •Knowledge is translated for non-experts within the team •Disciplinary grounding directly enables integrative or innovative outcomes

APPENDIX J Rubric – K2 - Integration Depth

Rubric - K2 - Integration Depth			
Score (0–3)	**Level**	**Descriptor**	**Indicators**
0 - None	No Integration	Only one discipline involved	•No integration
1 – Low	Minimal Integration	Output remains mono-disciplinary or only juxtaposes perspectives. Awareness or parallel contributions without real synthesis.	•Uses concepts/methods from only one discipline. •May acknowledge other disciplines but does not integrate them. •Parallel contributions: discrete, side-by-side elements without blending.
2 – Medium	Partial Integration	Some blending across disciplines, Basic integration.	•Emergence of hybrid features that combine disciplinary methods. •Design shows effort to cross boundaries but still retains visible disciplinary divides. •Problem addressed from multiple perspectives, though synthesis is limited.
3 – High	Advanced / Transformative Integration	Strong synthesis or creation of new frameworks. Advanced / **Transformative Integration**.	•Output demonstrates coherent, holistic integration. •Novel combinations of concepts/methods address the problem systemically. •Generates new frameworks, models, or paradigms that could not emerge from one discipline alone; potential for reuse/adaptation by others.

APPENDIX K Rubric – K3 - Advancement of Understanding & Novelty

Rubric - K3 - Advancement of Understanding & Novelty Rubric			
Purpose: To evaluate the *novelty* (*originality, Advancement of Understanding*) of the integrated solution (artifact) relative to existing approaches, methods, or practices within, and outside the discipline.			
Score	**Level**	**Descriptor**	**Indicators**
0 - N/A	No advancement or novelty	Solution shows no advancement or novelty	• Displays no advancement or novelty
1 – Low	Incremental	Solution is conventional; follows well-established approaches	• Relies mostly on known disciplinary or cross-disciplinary methods. • Adds little new insight beyond standard practices.
2 – Medium	Moderately Original	Some originality or creative recombination	• Introduces fresh twists on existing methods. • Combines ideas in ways that show creativity but remain familiar.
3 – High	Highly Original	Breakthrough or paradigm-shifting solution	• Creates a novel framework, method, or practice that substantially differs from established approaches. • Recognised potential for reuse/adaptation beyond the project context.

APPENDIX L Rubric – K4 - Learning and Capacity Building

Rubric – K4 - Learning and Capacity Building			
Score (0–3)	**Level**	**Descriptor**	**Indicators**
0 - None	No Demonstrable Learning	No clear evidence of new learning or capacity development beyond baseline disciplinary knowledge.	• No articulated new skills, insights, or conceptual shifts. • Work remains within pre-existing competencies. • No reflection indicating growth or transformation. • No evidence of skill transfer or perspective change.
1 – Low	Limited / Individual Learning	Evidence of new knowledge or skill acquisition at an individual level, but limited depth or transferability.	• Students report learning a new tool, method, or concept. • Learning remains task-specific and procedural. • Minimal evidence of perspective shift. • Limited articulation of how learning could be reused in other contexts.
2 – Medium	Shared / Applied Capacity Building	Demonstrable learning across team members; partial transfer of skills or perspectives beyond the immediate task.	• Teams articulate disciplinary insight gained from others. • Evidence of epistemic shift (e.g., increased empathy, reflexivity, systems awareness). • Skills applied beyond initial prototype iteration. • Reflection shows emerging ability to navigate ambiguity or integrate perspectives.
3 – High	Transformative Capacity Building	Significant cognitive, relational, or methodological growth with clear transfer potential beyond the course context.	• Evidence of sustained epistemic reflexivity and disciplinary boundary-crossing. • Demonstrated ability to independently apply integrated methods in new contexts. • Articulation of long-term professional or research impact. • Learning contributes to durable collaborative competencies (e.g., trust-building, navigating friction, systemic thinking).

APPENDIX M   Concept / Tool to TD Process Mapping

Below is a **complete mapping** of each concept/tool to the **TD Process Assessment Framework**, using the following structure (developed in Section 2.6.4):

- **TD Collaboration (Process Quality):** C1 Trust, C2 Communication, C3 Mutual Learning, C4 Conflict Handling (Friction), C5 Shared Problem Framing, C6 Equal Footing/Power/Fairness, C7 Team Critical Self-Awareness
- **TD Knowledge Creation (Tangible):** K1 Epistemic Grounding, K2 Integration Depth & Coherence, K3 Advancement/Novelty
- **TD Knowledge Creation (Intangible/Societal effects):** K4 Capacity Building, K5 Usefulness (salient/credible/legitimate/actionable), K6 Policy/Practice change

Each concept/tool pair is presented with the primary TD Collaboration dimensions it influences directly and the TD Knowledge Creation dimensions it enables downstream (i.e. the knowledge outcomes it supports).

Across the TD-SDT, tools were mapped to TD codebook dimensions based on their primary mechanism of action—whether strengthening collaborative process quality (C1–C7), enabling integrative knowledge creation (K1–K3), or supporting learning and societal usefulness (K4–K6).

Concept / Tool to TD Process Mapping Table					
Tool	**Primary C Dimensions**	**Enabled K Dimensions**	**Rationale**	**Key References**	**Notes**
Ambiguity – Open Challenge	C5, C4, C7	K3 (strong), K2, K4	Designed openness; forces negotiation of framing and tolerance of uncertainty.	(Cross, 2006; Dorst, 2019; Schon, 1983)	Catalyst tool; can fragment teams if trust/structure are weak.
Art Signature Pedagogies	C2, C3, C7	K2 (strong), K1, K4	Normalises critique, iteration, and aesthetic judgment within collaborative inquiry.	(Eisner, 2002a; Hetland, 2013)	Stabilises reflective inquiry through critique/iteration; legitimises aesthetic judgment.
Art Storytelling – Data Visualisation	C2, C5	K5 (strong), K2, K1, K3	Translates data into narrative/aesthetic form; enhances societal salience and intelligibility.	(Cairo, 2016; Kosara, 2016)	Strong for salience/legitimacy with external audiences; integrates affect + evidence.
Art Storytelling – Pixar in a Box	C2, C3, C5	K2, K5, K4, K3	Encourages narrative reframing and perspective-taking (Bruner J., 1990; Henriksen & Group, 2018; Her Huth, 2017)	Perspective-taking and narrative reframing; useful for aligning intent and meaning.	
Art – Speculative Futures	C5, C4, C7	K3 (strong), K2, K5, K4	Projects alternative futures; destabilises present assumptions and expands conceptual space.	(Boden, 2004; Dunne & Raby, 2013)	High-ambiguity novelty driver; benefits from critique structures to prevent drift.
Boundary Objects / Prototyping	C2, C5	K2 (strong), K1, K3	Materialises ideas for coordinate, 2002; Star & Griesemer, 1989)	Primarily a coordination mechanism; does not guarantee deep integration on its own.	
Building Trust – Vulnerability (Create & Protect)	C1, C2, C6	K4 (strong), K2 (indirect)	Creates psychological safety and enables epistemic risk-taking.	(Edmondson, 2012; Levin & Cross, 2004)	Relational prerequisite for productive friction and epistemic risk-taking.
Mutual Learning / Teach-a-Skill	C3, C2, C6, C5	K4 (strong), K1, K2	Redistributes expertise and activates reciprocal learning.	(Lave & Wenger, 1991; Wenger, 1998)	Redistributes expertise; improves equal footing and shared vocabulary.
Creativity – Abstracting (Metaphor)	C2, C3, C5	K3 (strong), K2	Enables cross-domain mapping and lateral reframing.	(Henriksen & Group, 2018; Lakoff & Johnson, 1980; Root-	Enables cross-domain mapping; often precursor to transformational reframing.

				Bernstein & Root-Bernstein, 2001)	
Creativity – Patterning	C3, C5	K2 (strong), K3, K1	Reveals structural analogies; supports integrative synthesis.	(Henriksen & Group, 2018; Root-Bernstein & Root-Bernstein, 2001)	Supports analogy-seeking and structural comparison; bridges toward synthesis.
Creativity – Perceiving (Formal Analysis)	C2, C7	K1 (strong), K2	Deepens disciplinary grounding and attentional rigor.	(Henriksen & Group, 2018; Root-Bernstein & Root-Bernstein, 2001)	Sharpens observation and shared descriptive language; supports grounding.
Creativity - Embodied Thinking	C1, C2	K4 (strong), K2, K3	Grounds cognition in lived experience and affective engagement.	(Henriksen & Group, 2018; Root-Bernstein & Root-Bernstein, 2001)	Enhances affective engagement and retention; useful when verbal language is limiting.
Creativity - Playing	C1, C3, C4, C7	K2 & K3 (strong), K4	Creates bounded exploratory space that lowers risk, destabilises disciplinary rigidity, & enables analogical recombination prior to integrative consolidation.	(Boden, 2004; Henriksen & Group, 2018; Sawyer, 2004)	Temporarily suspends rigid disciplinary evaluation criteria, lowers defensive behaviour.
Lego® Serious Play	C2, C4, C6	K2 & K4 (strong), K3	Externalises thinking, democratises voice, and surfaces assumptions.	(Kristiansen & Rasmussen, 2014)	Democratises participation; makes tacit assumptions visible through shared models.
Productive Friction (Slowing)	C4, C7	K2, K3, K4	Prevents premature convergence and sustains reflective tension.	(Jehn, 1995; Stengers, 2005)	Prevents premature convergence; requires trust and facilitation to remain generative.
Reflexivity – Disciplinary Self-Awareness (ITP Metrics)	C7, C6	K1 (strong), K2, K4	Makes epistemic positioning explicit and reduces invisible hierarchy.	(Gardiner, 2020; Schon, 1983)	Makes epistemic positioning explicit; helps anticipate role / communication tensions.
Reflexivity – Equal Footing & Humility	C6, C7, C1, C2	K2, K4 (strong), K5	Reduces epistemic dominance and supports equitable negotiation.	(Gardiner, 2020; Pohl & Hirsch Hadorn, 2007)	Counters epistemic dominance; supports legitimacy/justice in collaboration.
Reflexivity – Multiple Intelligences	C3, C7, C6	K2, K4 (strong), K1	Legitimises diverse capabilities and supports role fluidity.	(Gardiner, 2020; Gardner, 1993)	Broadens what counts as competence; supports recognition of diverse contributions.

Symbolic Infrastructure – (Exhibition/art installation)	C1, C2, C5	K5 (strong), K4 (strong), K6	Embeds collaboration within shared meaning systems and collective identity.	(Dewey, 1934; Haraway, 2013; Maggs, 2024a)	Cultural embedding via public-facing artifacts; supports longer-horizon impact.
Synthesising (Integration)	C5, C3, C2	K2 (strong), K3, K1, K5	Consolidates coherent TD synthesis.	(Klein, 2010a; Lang et al., 2012)	Deliberate consolidation step; benefits from prior coordination + reflexivity.
Transformational Creativity	C5, C3	K3 (strong), K2, K5	Reconfigures conceptual space and expands possibility horizon.	(Boden, 2004; Dorst, 2019)	Conceptual restructuring; typically enabled by metaphor, patterning, speculation.
Philosophy – Concepts for reflections (time & space)	C7, C5, C4, C3	K2 (strong), K3, K5, K4	Surfaces ontological and epistemological assumptions; restructures problem framing; deepens integration beyond procedural coordination.	(Dorst, 2019; Klein, 2010a; Stengers, 2005)	Philosophical concepts specifically operate at the **meta-epistemic layer** — they interrogate *how* knowledge is structured, not just *what* is being created
Co-creation with Generative AI	C2,C5,C7, C4,C3	K2, K3, K4	AI operates as epistemic mediator and generative amplifier; accelerates reframing and conceptual blending; requires reflexive governance to avoid shallow integration.	(S. Bender, 2025; S. M. Bender, 2023; Floridi et al., 2018; Luckin & Holmes, 2016; Schon, 1983)	Gen AI is an epistemic amplifier. Without reflexivity leads to shallow synthesis. With reflexivity & friction leads to high K2/K3

APPENDIX N Semi-Structured Interview Questions

Iteration 3

Semi-structured interview questions:

1. Could you introduce yourselves and your discipline?
2. Could you talk about your summer project?
3. How did the artists and engineers connect?
4. Can you describe what your projects were?
5. How many people were in the team?
6. How did you come up with the main idea for your project?
7. Could you describe the process from technical prototype to artistic final project?
8. Were you speaking the same language initially? Give examples.
9. What were your big learning experiences?
10. Was there any support for you during this process?
11. What would you say to yourself, if you were able to go back to the beginning of the project?

Iteration 4

Semi-structured interview questions:

1. Could you introduce yourselves and your discipline?
2. Why did you sign up for this course?
3. Can you tell me about your learning experience so far?
4. What skills have you improved over this course?
5. What are the difficulties you encountered?

APPENDIX O Student Reflections Questions

Student Reflection Journal Questions

Iterations 1-4 no reflection journal requested from students

Iteration	Questions
5	Journal #1 (Blog 1) – Reflection (week 2)
	Objective: document the individual experience in the class and explore personal growth, creative evolution, the learning and the challenges of the course. Reflect on the following themes: Overall progress and learning, personal growth, artistic (theme & Medium), creativity (idea generation), client, project development, social innovation & entrepreneurship, team dynamics & management, technology. Teaching: What did you appreciate the most so far about this course? Why? What did you appreciate the least so far about this course? Why? What recommendations would you have about this course?
5	Journal #2 (Blog 2) – Formal Analysis (week 5)
	Present a formal analysis of an artwork seen at the National Gallery of Canada
5	Journal #3 (Blog 3) – Reflection (week 6)
	Same questions as Blog 1
5	Journal #4 (Blog 4) – ITP Metrics results (week 9)
	Blog 4 focuses on your ITPM results. You can choose to answer the questions of each of the assessments (peer, conflict management, personality, leadership) or you can reflect on each in a free format. The objective is to 1. help you understand your strength and your weakness 2. improve your individual and team performance in this project 3. improve your future personal and team performance.
5	Journal #5 (Blog 5) – Reflection (week 12)
	Same questions as Blog 1
6	Journal #1 (week 4)
	Set your personal learning goals for this course as follows: 1. As a team, discuss the project and set your team goals. 2. Agree as a team what does success look like for you. Are you setting goals that must be met or are they guidelines that will be reassessed? We need to study ourselves first, to become experts on our own potential: 3. Once you know what part you will be doing as an individual, start by writing an inventory of your personal strengths and weaknesses related to your role in the project.
6	Journal #2 (week 6)
	Write a design reflection by sharing a story of when you were surprised, perplexed, or intrigued by an experience you had during the project design. Your audience for this reflection is a future STEAM Design student. You are writing a blog post for them to read.
6	Journal #3 (week 9)
	How do you believe your own academic/professional/personal framing impacts your interpretation and understanding of the challenges in the course? How do you believe your peers' academic/professional/personal framings impact their interpretation and understanding of the challenges in the course?

	Were there particular Knowledge, Skills, Values (KSVs) that prompted group discussions, challenges and stood out and stimulated your group's imagination or interest? Explain.
6	Journal #4 (week 12)
	Did you meet your personal learning goals for this course as identified in Journal Entry #1? What are your key takeaways from this course?
7	Journal #1 (week 4)
	Objectives: • Set your personal learning goals for this course. • Make an inventory of your strengths and weaknesses. • Get to know yourself. Questions: 1. What are you hoping to get out of this course? 2. Knowing about the projects now, start by writing an inventory of your personal strengths and weaknesses related to the projects as you understand them today. 3. Identity how you get into the right frame of mind to be creative. 4. Figure out how you will measure your own objectives and key results (Personal-OKR).
7	Journal #2 (week 6)
	Objectives: • Get to know yourself better. • Get to know your team better. Questions: 1. Present the results of your Multiple intelligence test. 2. Present the results of your Conflict Management Style test. 3. As a team, develop and present a common table of team SWOT, Intelligences, conflict Management styles (one for the team) 4. Present your personal interpretation of that table.
7	Journal #3 (week 12)
	Objectives: • To reflect on the contributions each of your interdisciplinary peers/groupmates makes to the group work you are completing in the course • To reflect on whether you achieved what was set forth in your OKR analysis. Questions: Did you meet your personal learning goals for this course as identified in Journal Entry #1? What are your key take aways from this course? How do you believe your own academic/professional/personal framing impacts your interpretation and understanding of the challenges in the course? How do you believe your peers' academic/professional/personal framings impact their interpretation and understanding of the challenges in the course Were there particular KSVs that prompted group discussions, challenges and stood out and stimulated your group's imagination or interest? Explain.

APPENDIX P Iteration 2 Artifacts Collected

Artifacts

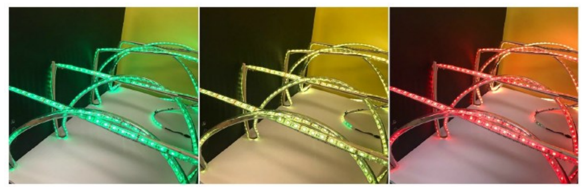
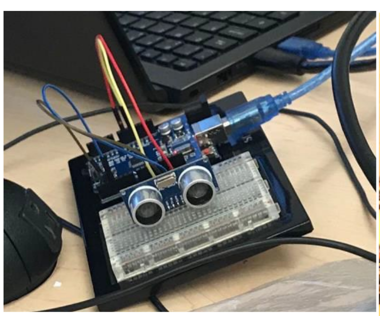
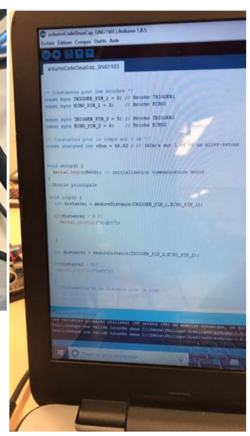
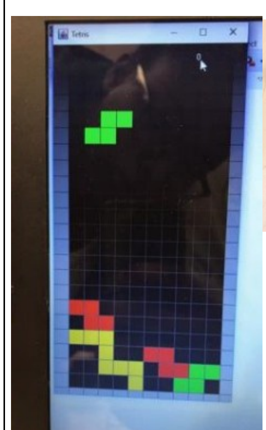
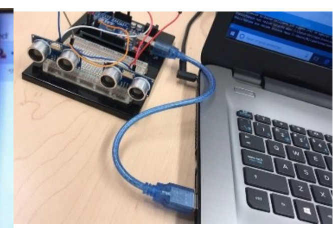
In iteration 2, eight engineering teams developed interactive art installations designed for the uOttawa STEAM building as shown in Together, these projects demonstrate how engineering students leveraged *interactivity, embodiment, and basic aesthetic strategies* to transform everyday actions—walking, touching, speaking, and playing—into sensory installation prototypes intended to foster creativity and social interaction within shared public spaces of the STEM building.

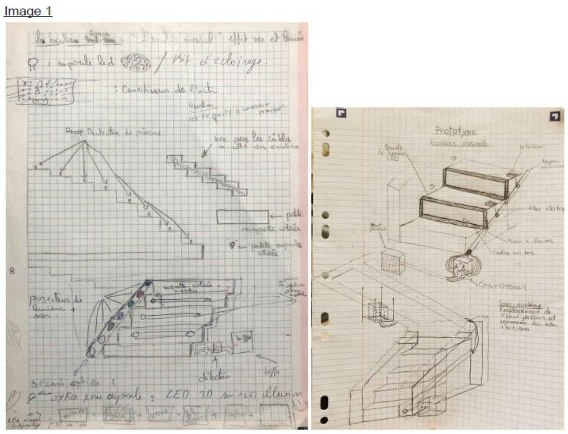
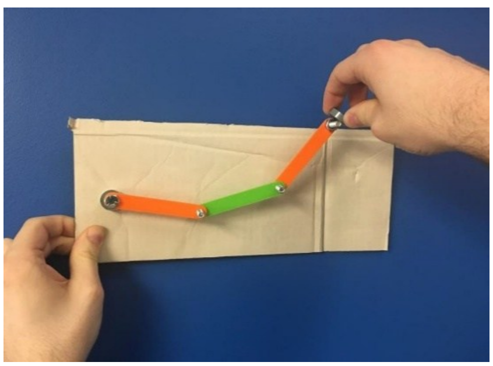
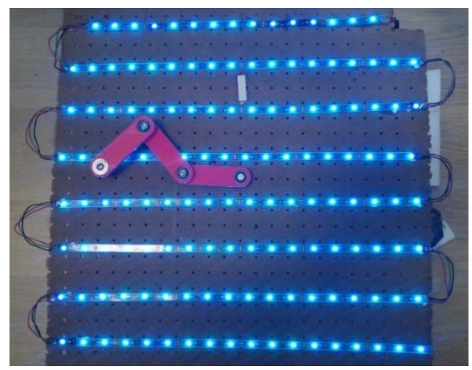
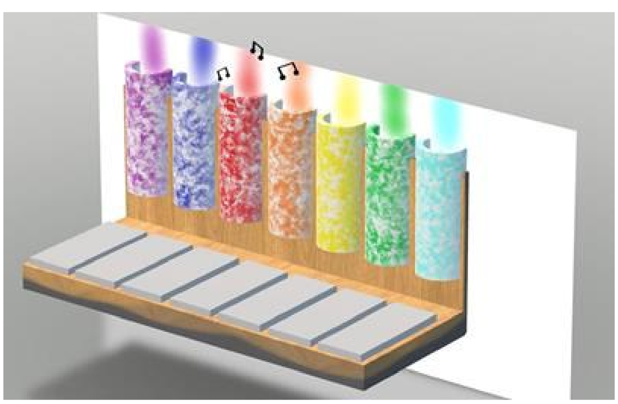
All teams successfully produced artifacts responding to the creative brief. However, while prototypes were technically competent, most prioritised *functional performance over aesthetic refinement*, a pattern consistent with projects developed within a single-discipline engineering context.

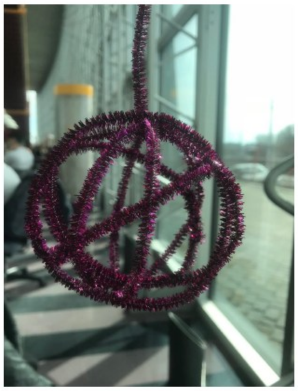
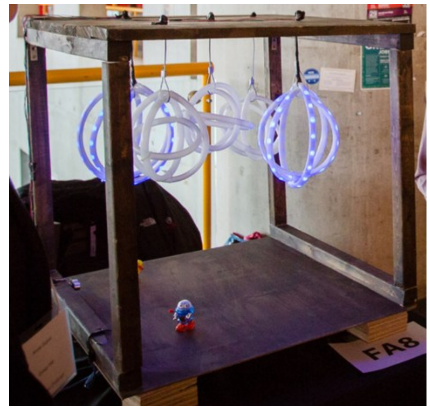
Table 10. Team 1 presented ***Balls on the Wall*** which transformed a corridor into a playful passage where stepping on floor switches lighted up wall-mounted balloons. Team 2 presented ***Ambiance*** which turned sound into a dynamic spectrum of shifting LED colors along a spiraled tunnel. Team 3 offered the ***Interactive Screen Game*** which invited full-body movement to control falling shapes in a digital play experience; Team 4 designed a ***Musical Staircase*** which converted ordinary stairs into a musical instrument, where infinity-mirrors lighted up and a musical note played when triggered on each step. Team 5 presented the ***Triple Pendulum Chaos*** which visualised nonlinear physics through unpredictable kinetic motions and trails on an LED panel. Team 7 offered a ***Giant Interactive Piano*** which allowed visitors to step on oversized keys to create music together. Team 8 presented ‘***Mouvement' DEL*** suspending spherical luminous forms overhead that awakened in response to nearby motion. And Team 9 offered ***Brain*** which used a touch-activated plasma sphere to animate glowing cable “synapses,” linking human gesture to neural metaphor.

Most teams produced prototypes responding to the creative brief. While technically competent, most outputs prioritised functionality over aesthetic dimensions. This situation was to be expected from on single discipline engineering group.

Intermediary Prototypes and Conceptual Designs`

Team 1 - P1 	Team 1 – P3 
Team 2 -P1 	**Team 2 -P3** 
Team 3 -P1  	**Team 3 -P3**  

Team 4 – P1 	Team 4 – P3 Musical Stairs 
Team 5 – P1 	Team 5 – P3 
Team 7 – P1 Piano 	Team 7 – P3 Piano  ***Figure 6*** *– Produit final*

Team 8 – P1  Prototype 1	Team 8 – P3 
Team 9 – P1 	Team 9 – P3 

APPENDIX Q Iteration 4 Artifacts Collected

Team 6 - Digital Entanglement

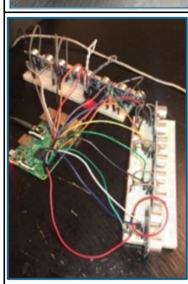
Project Focus

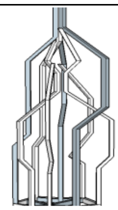
The project, titled Digital Entanglement, was an integrated engineering-art sculpture designed to incorporate energy or technology and be interacted with for a touring recycled art show. The team chose sound as the technological focus of the sculpture.

Artistic Statement

The project was designed to explore technology and arbitrary sounds related to its narrative. Following initial client feedback that noted a lack of narrative, the team developed the concept that the frame's bends represent different lines of communication coming from separate areas and converging together.

Intermediary Prototypes and Conceptual Designs`

Prototype	Description
	P1. This was the initial model, made from common household items such as skewers and popsicle sticks, which kept the budget at zero. Its purpose was to transform the design from a sketch into a physical, comprehensive model showcasing the entire sculpture for the first client meeting.
	P2. This was a focused prototype on the technology. It provided the first look at the electronics, utilising a Raspberry Pi, ultrasonic sensors, and a breadboard to create a circuit. This stage allowed for testing individual parts and figuring out any bugs.

	Artifact. This was a comprehensive model of the frame. It was constructed in full scale using recycled desks and later incorporated all the components of the sculpture.
	P4. The final prototype, **Digital Entanglement**, is an interactive sculpture that responds to a viewer's proximity. As users move from four meters away to directly beside the piece, layers of sound progressively overlap, with each threshold triggering a new auditory element. The curved structure visually represents intersecting communication lines, reinforcing the theme of interconnected digital relationships.

Desired impact on the audience:

The primary desired impact was to create an **i**nteractive piece of art that could be included in a touring recycled art show. The interaction allows users to trigger sounds based on their proximity to the piece. The sculpture was successful in achieving a positive impact, as client feedback was positive and the sculpture was asked to be part of the Recycl'art tour during the summer, meaning it surpassed initial expectations.

Team 7 - Distorted View

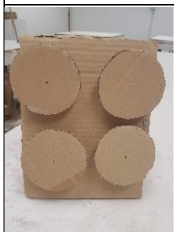
Project Focus

The project "Distorted View" was an interactive art sculpture created through a collaboration between engineering and art students for the Recycl'Art art exhibition. The final design, which evolved from the "Rotating Umbrellas" concept, used kinetic function and reflective surfaces.

Artistic Statement

The core narrative emphasises promoting recycling and the collaboration between engineering and art disciplines. The title "Distorted View" stems from the design's use of rotational dynamics and reflective surfaces (the recycled CDs). This visual combination captures the viewer's eye while they interact, leading to an interesting distortion of the viewer and light.

Intermediary Prototypes and Conceptual Designs`

Prototype	Description
 	P1. The first prototype featured two physical models to explore the project’s direction: a 3D-printed version showing the full planned layout, including wiring, and a cardboard model with four rotating discs mounted on toothpicks. The cardboard version allowed the team to test basic functionality and demonstrate how movement in front of the sculpture would activate the spinning elements.
	P2. The second prototype focused on testing interactivity and electronics, using an Arduino circuit to adjust a motor’s speed based on proximity sensing. A larger disc structure was built, incorporating recycled CDs to begin exploring the visual direction of the final sculpture while validating key functional components.
	P3. The final prototype brought all components together at full scale, using recycled plywood for the backdrop and adding supports and recycled CDs to refine the disc elements. After discovering the main disc was too heavy for the motor—and prioritising size over rotation per instructor feedback—it was fixed in place, while the circuit was soldered for exhibition-ready stability. The final prototype, Distorted View, remained over 80% recycled material and combined an ultrasonic sensor with Arduino control to trigger motorized motion in the smaller disc as viewers approached, using reflective, kinetic elements to distort perception and highlight shifting perspectives.

Desired impact on the audience

The client, Recycl'Art, aimed for the art piece to "touch the life of others". The desired impact was for the sculpture to be innovative, interactive, and eye-catching. It was intended to capture the attention of visitors to the exhibition and leave a positive impact on them by making an emotional connection.

Team 8 - Impact

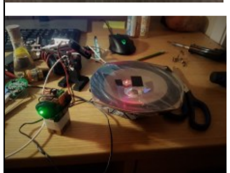
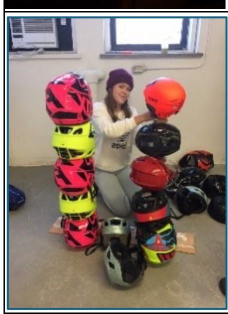
Project Focus

The project, titled "Impact," was an interactive STEAM sculpture created for the Recycl'art and Traces Arts Visuels collaborative exhibition, commissioned to relate to themes of energy, technology, and the impact of words.

Artistic Statement

Impact explores the power of words through energy, interaction, and sound. Constructed from damaged, discarded helmets—objects meant to protect the brain—the sculpture invites visitors inside to discover a responsive laser system that transforms their voice into shifting light patterns. By contrasting its rugged exterior with a dynamic inner life, the work prompts reflection on how discarded materials—and the ideas they once protected—can still carry meaning, urging viewers to reconsider their assumptions about waste and value.

Intermediary Prototypes and Conceptual Designs`

Prototype	Description
 	P1. This stage combined a full physical mock-up with a targeted functional prototype. **Prototype 1.1** demonstrated the planned structural layout and how the helmets would attach to the frame. **Prototype 1.2** tested the laser-based visual system, using a mirror fragment mounted on a vibrating membrane above a speaker so the reflected laser could generate shifting patterns in response to sound frequencies.
	P2. The next prototype scaled the structure to a three-foot free-standing form to test helmet stacking and attachment with more realistic materials. Transitioning from lightweight Styrofoam to wood and actual helmets revealed important structural considerations, such as placing heavier motocross helmets at the bottom and lighter ones above. This stage also showed that wood would not withstand repeated assembly and disassembly required for exhibitions.

	P3. The final full-scale prototype used a modular carbon-steel frame with parabolic supports and securely mounted reclaimed helmets, achieving over 80% recycled content. Integrating the refined laser system from earlier testing, the design filtered sound frequencies to reduce background interference and enhance user interaction. Titled Distorted View, the installation invites participants to step inside the helmet-lined structure, where their voices are captured by a microphone that drives a vibrating mirror attached to a speaker. This movement causes the laser beam to shift and ripple overhead, creating dynamic visual patterns that reveal how human input alters both the auditory and visual environment.

Desired impact on the audience:

The installation's primary goal was to create an aesthetically engaging, energy-driven interactive experience. By inviting visitors inside to activate laser patterns that mimic brain activity through sound, the piece highlights the interconnectedness between individuals and their environment. This dynamic visual response underscores the work's core message about the hidden energy and relationships that shape our world.

Team 10 - Fallen

Project Focus

Fallen is a sculptural installation made from over 80% recycled materials aims to encourage audiences to reflect on their environmental impact and the importance of sustainability.

Artistic Statement

The sculpture's core theme is ecological disruption, illustrated through a fallen mushroom with trees growing from its cap—a reversal of nature's typical order. Root-like cords made from discarded electronics underline the idea that if our connection to the environment were as strong as our attachment to devices, ecosystems would be healthier. This abstract yet striking visual metaphor effectively communicates the human-driven disturbances shaping the natural world.

Intermediary Prototypes and Conceptual Designs`

Prototype	Description

	P1. The first physical prototype emphasised stability, testing the design concept and ensuring the intended theme was clearly communicated. While the structure effectively demonstrated the idea, feedback suggested shifting from a vertical to a horizontal orientation to improve anchoring and performance in windy conditions. This early iteration confirmed potential stability challenges and informed necessary design adjustments moving forward.
 	P2. The second physical prototype focused on creating a free-standing, weather-resistant structure by assembling the metal column base and carving the mushroom top from Styrofoam. This stage tested material cohesion, sensor placement, and lighting functionality, with success defined by the structure's ability to stand independently, withstand wind up to 60 km/h, and be disassembled within 15 minutes. Feedback confirmed that the prototype was structurally strong, visually compelling, and effectively conveyed the project's message.
	P3a. The third and final comprehensive prototype refined the full-scale structure by integrating both electronic and aesthetic features. The mushroom cap was weatherproofed with repurposed canvas banners, while recycled coroplast fins beneath the cap added visual interest and housed an LED lighting strip. Parasitic "tree" forms were embedded into the structure, and coiled power cords created root-like elements at the base. This stage also tested motion-activated lighting and wind stability up to 60 km/h, ensuring the installation was both durable and functionally interactive.
	P3b. The final prototype, **Fallen**, depicts a toppled mushroom with illuminated tree forms emerging from its cap, symbolising regeneration from decay. Built from over 80% recycled materials and designed for portability, the sculpture features coroplast fins, scavenged cord "roots," and laser-cut acrylic trees lit by LEDs. Three ultrasonic sensors around the base control color responses—each triggering a unique hue or cycling combinations when activated together—with cycling speed changing based on viewer proximity, creating an interactive reflection on environmental fragility and renewal.

Desired impact on the audience

The installation aims to attract viewers through its striking form and intuitive interactivity while inspiring reflection on environmental responsibility. By linking light behaviour to audience presence—faster and more colorful responses with multiple participants—it encourages shared engagement, reinforcing the idea that collective action is essential to creating meaningful ecological change.

Team 11 - Vortex

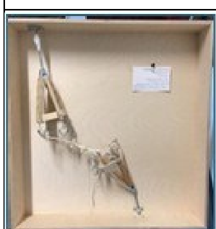
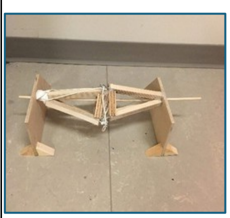
Project Focus

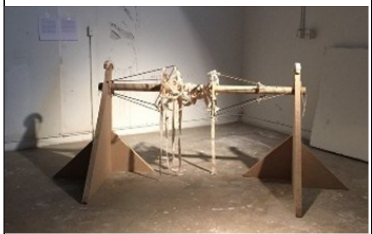
The project, titled Vertex, was a human interactive public sculpture that successfully used 100% recycled materials and kinetic energy.

Artistic Statement

The artistic intent behind Vertex is to symbolise the blind and ongoing destruction humans inflict on the environment. By requiring two people to physically pull the structure together, the horizontal design makes the metaphor more explicit—our actions, even when unnoticed, contribute to environmental collapse. Blending engineering precision with artistic expression, the sculpture's true impact lies in its meaning rather than its mechanics, urging viewers to recognise their role in shaping—or damaging—the world around them.

Intermediary Prototypes and Conceptual Designs`

Prototype	Description
	P1. The first prototype featured two vertical pyramidal structures mounted to the ceiling and wall, demonstrating the concept of the forms moving toward and away from each other. While the motion was successful as a proof of concept, feedback emphasised the need for clearer symbolic meaning and stronger human interactivity to ensure viewers could more fully engage with the installation's intended message.
	P2. The second prototype introduced a major shift from a vertical to a horizontal layout, allowing the two pyramids to move along a central axle for greater stability and clearer symbolic expression. Originally envisioned with a hand crank, the team later explored more interactive movement options to better engage viewers. This redesign helped strengthen the metaphor of environmental disruption while aligning with client feedback for improved interactivity and meaning.

	P3. Vertex is a fully human-interactive sculpture made entirely from salvaged and recycled components. The piece consists of two metal pyramidal structures mounted on a hollow cardboard axle between reclaimed wooden walls, requiring two participants to pull handles from either side to slide the pyramids together into a diamond form. This simple rope-driven mechanism emphasises collaboration while demonstrating how engineering fundamentals and sustainable practices can work together to create meaningful art.

Desired impact on the audience:

The design prioritised human interaction to make the environmental symbolism tangible—requiring two participants to pull handles to activate the sculpture and metaphorically reveal humanity's role in environmental change. The piece was well-received on Design Day, with viewers noting the compelling blend of functionality and meaning, reinforcing the idea that collective human action is essential in shaping the environment's future.

Team 12 - Wave of Consciousness

Project Focus

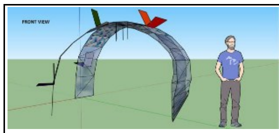
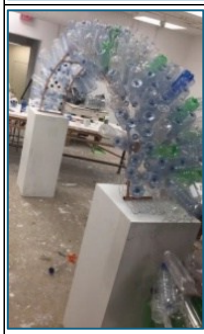
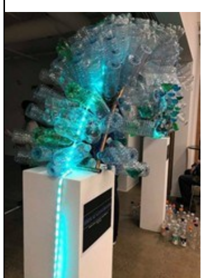
The project, titled the "**Wave of Consciousness**," was an interactive, original sculpture made from at least 80% recycled materials, intended to bring **awareness to plastic pollution in our oceans**.

Artistic Statement

The project was designed with a powerful theme in mind. The theme is meant to bring awareness to plastic pollution in our oceans. The use of recycled plastic water bottles throughout the structure helped to invoke messages that were meaningful and relatable.

Intermediary Prototypes and Conceptual Designs`

Prototype	Description

 	P1. The first prototype explored a dome-like structure made from recycled plastic water bottles to test stability and coloring methods, including acrylic gel, tinted water, and polyethylene. Client feedback led the team to select bottles filled with colored water as the most practical and thematically aligned option, while also prompting design changes to improve outdoor structural stability.
	P2. The second prototype shifted to a wave-shaped structure, creating a 3-foot physical model to assess durability, construction risks, and visual appeal. Different attachment methods—hot glue, fishing rope, wires, and plastic knots—were tested, revealing that hot glue was unsuitable for long-term stability or transport. The revised form was approved by clients, and further exploration of stronger fastening and framing methods followed.
	P3. The third prototype successfully integrated structure and electronics using a metallic frame and chicken wire to mount recycled plastic bottles, with LED strips controlled by Arduino for lighting tests—proving far more durable for outdoor use. The final installation, Wave of Consciousness, retained this wave-shaped form and predominantly recycled construction, with plans for future motion-responsive lighting to enhance interactivity. Designed for easy transport and display, the piece aimed to visually communicate rising awareness of sustainability and environmental stewardship.

Desired impact on the audience:

The sculpture aimed to be highly interactive and visually striking, capturing audience attention while promoting environmental awareness. Its success was reflected in enthusiastic responses during Design Day and its second-place recognition at the Art Exhibit, affirming the team's goal of creating an engaging and impactful piece for the client.

Team 14 - Orbital Simplicity

Project Focus

The project, titled "**Orbital Simplicity**," successfully integrated art and engineering to create an interactive sculpture, modeled after a gyroscope, which surpassed the requirement by utilising 100% recycled materials except for the electronics and minor fasteners used in the centre sphere.

Artistic Statement

The sculpture draws inspiration from a gyroscope, using human-generated motion to spark imagination and creativity. Made from recycled materials, it demonstrates how discarded objects can be transformed into expressive art and invites viewers to engage physically with the piece. By evoking associations with childhood play and the wonder of outer space, the work encourages audiences to reconsider waste as a source of creative potential.

Intermediary Prototypes

Prototype	Description
	P1. This prototype was a small-scale model designed to test the structure and working parts of the final design. It was constructed using parts from a toy bicycle and expired medical equipment, bound with clear tape. A primary flaw was weight imbalance, causing the structure to fall sideways because the top was heavier than the base.
	P2. This prototype improved stability and scale by incorporating larger recycled components, including a bicycle wheel and a repurposed office chair base intended for outdoor anchoring. The central sphere was upgraded using a recycled globe weighted on one side to spin more smoothly. Client feedback at this stage encouraged adding interactive technology, specifically lighting that would activate only through human-generated motion.
	P3. The final refinement stage focused on improving movement and integrating technology by smoothing the spinning rings and embedding an Arduino-controlled motion sensor and battery into the centre sphere. The completed prototype, Orbital Simplicity, is a gyroscope-inspired interactive sculpture built from recycled materials such as metal rods, a bicycle wheel cover, and an office chair base. Users manually spin the nested rings, which can rotate 360° in multiple planes, and their motion triggers wire lights inside the central sphere—illuminating only when movement is detected and turning off as it ceases—making the viewer's physical energy the driving force of the artwork.

Desired impact on the audience

The primary goal of Orbital Simplicity was to entice audiences through active participation, using human motion as the energy source that brings the sculpture to life. By completing the kinetic circuit themselves, viewers trigger the sensor and illuminate the central sphere, making visible their immediate action.

APPENDIX R Iteration 5 Artifacts Collected

We present here the artifacts collected in iteration 5 and the evolution of the intermediary prototypes produced by each team, with an accompanying short description for each element.

Team 1 – Deer Squad – Noise Censorship

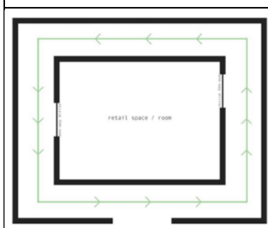
Project Focus

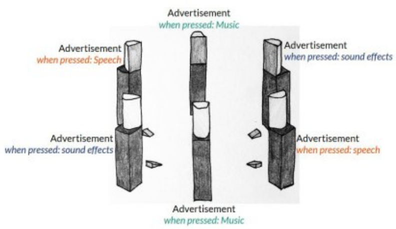
The project, titled "Noise Censorship", focuses on sound art to force viewers to confront their relationship to consumerist structures in society.

Artistic Statement

The installation aims to expose the hidden consequences of overconsumption by reversing the usual disconnect between consumer behaviour and its impacts. Six speakers arranged in a circle shift from playing polished advertisements to revealing disturbing narratives about sweatshops, the Rana Plaza collapse in Bangladesh, and global textile waste—but only when audience members collectively press sewing machine pedals. This sustained, shared effort symbolises the emotional labor required to confront uncomfortable truths in a noise-saturated society, challenging viewers to acknowledge their role in a cycle they rarely see.

Intermediary Prototypes and Conceptual Designs

Prototype	Description
	P1. The first concept, **Retail Space (The Shed),** proposed a life-sized store façade that lured visitors inside, only to trap them in a narrow tunnel with limited views into a seemingly glamorous shop—hinting at hidden labor and waste behind consumer culture. However, feedback indicated the experience would likely feel underwhelming and impractical to build, leading the team to move away from this approach.
	P2. The **Textile Wave** concept envisioned three large quilts made from textile waste, moving like waves to evoke feelings of entrapment and highlight consumerism's environmental impact. However, feedback indicated the idea lacked clarity and narrative focus, prompting the team to shift back toward sound-based storytelling to more effectively communicate the cyclical nature of consumption.

	P3. The first functional prototype of **Noise Censorship** used three floor-placed speakers controlled by Isadora software, each switching between two sound sources focused on the Rana Plaza tragedy in Bangladesh. Feedback encouraged broadening the audio content, balancing volume and tone across tracks, and considering visual or spatial adjustments. The team chose to keep the speakers upright to preserve a human-like presence, reinforcing the installation’s critical message.
	Artifact. The final installation, **Noise Censorship**, features six speakers arranged in a circle with sewing pedals placed in front of each one. When a pedal is unpressed, the speaker plays corporate ads from companies with unethical practices; pressing the pedal switches the audio to reveal hidden narratives about environmental harm and exploitation. When all six pedals are pressed at once, the tracks align into a unified message, symbolising collective action. The system is controlled through Isadora software and a central Arduino, routing specific audio channels to individual speakers.

Desired impact on the audience:

The desired impact of the "Noise Censorship" sound installation is to force viewers to confront their own relationship to consumerist structures present in society. The goal is to facilitate a transition in the user's thought process when engaging in consumer activities. By exposing the user to the "bigger story" behind mass consumption, the team aims to allow the consumer to consider their actions more carefully. This is achieved by requiring a sustained, collective, and cumulative effort (pressing all six pedals) to bypass the "censorship by noise" (the advertisements) and reveal the underlying narrative of the exploitative costs of consumerism.

Team 2 – The STEAM Punks– The Creature

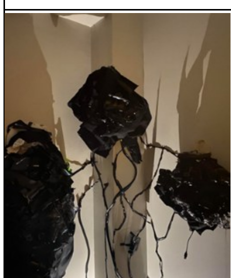
Project Focus

This installation, entitled "The Creature", created by The Steam Punks, centred on the theme of **pollution** and the long-term effects of human waste on the planet.

Artistic Statement

The installation confronts viewers with a creature-like form made of waste to highlight the growing environmental damage caused by human consumption and the emotional disconnect people often feel toward pollution. Rather than relying on statistics, the piece invites curiosity and discomfort as audiences encounter a living, invasive entity “blebbed” from humanity—something that moves, grows, and should not exist. Inspired by Ingrid Bachmann’s *Pelt (Bestiary)*, the work aims to provoke awareness by making the consequences of human waste impossible to ignore.

Intermediary Prototypes and Conceptual Designs

Prototype	Description
	P1. The first prototype established the initial aesthetic by creating textured models from recycled garbage and cardboard, some of which were spray painted black. A sound component was added using slowed and pitch-shifted recordings of the trash materials. Feedback from this stage led to incorporating black paint more prominently in later designs.
	P2. The second prototype emphasised motion and interactivity by creating abstract, fabric-covered forms inflated by garbage bags and powered by an Arduino-controlled fan to simulate breathing. Multi-layered audio combined ambient tones with triggered garbage sounds when viewers stepped on a contact microphone. Feedback revealed that the breathing effect was too subtle and the sound too calming, prompting structural and sonic adjustments for the final design.
	Artifact. The final installation features three wall-mounted “breathing” blobs made from recycled garbage, fabric, and wood, animated by Arduino-controlled fans to create sudden, unsettling gasps. Supported by Isadora software, the soundscape layers looping ambient noise with aggressive sub-bass tones, sharp string textures, and triggered trash sounds that respond to a viewer stepping nearby, forcing them to confront their impact on this unsettling creature of waste.

Desired impact on the audience

This sonic rupture is meant to make the viewer feel their direct impact on the fragile creature before them. By transforming their presence into a source of disturbance, the installation confronts them with the unsettling reality of the pollution humans create. The goal is to provoke a moment of discomfort, recognition, and environmental self-awareness—an embodied realisation that even small actions disrupt the world we inhabit.

Team 3 – Lpsum– Kinology

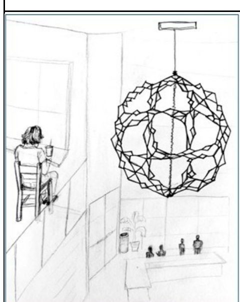
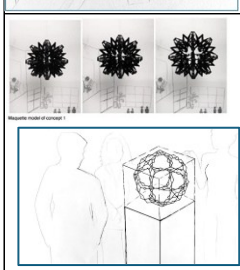
Project Focus

This installation, titled **"Kinology"** and created by The Lpsum team, examines the growing disconnect between human actions and their environmental consequences. By highlighting how constant exposure to ecological crises can lead to apathy, nihilism, or altruistic burnout, the project challenges viewers to re-engage emotionally and reflect on their impact.

Artistic Statement

Kinology is an interactive art installation designed to provoke reflection on humanity's impact on the environment by treating a Hoberman sphere as a living entity confined in a plexiglass box. By responding to audience proximity with shifting "emotional" behaviours, the piece creates a moment of intrigue that reveals our forgotten symbiosis with the natural world, using the unsettling contrast between the sphere's breathing-like motion and its synthetic, lifeless form to challenge perceptions of what is alive and what we control.

Intermediary Prototypes

Prototype	Description
	P1. The first prototype envisioned a large suspended Hoberman sphere that would expand and contract in response to the number of nearby viewers, symbolising human impact on the environment. However, the idea was ultimately abandoned due to safety concerns and the high cost and time required to produce and suspend such a large kinetic structure.
	P2. The second prototype introduced the core concept for the final design: a smaller Hoberman sphere confined inside a clear case atop a plinth, evoking a captive animal on display. Programmed to expand and contract more rapidly as visitors approached, it was further styled with signage and grass to reinforce the theme of human control over another living entity.

Artifact. The final Kinology prototype envisioned a responsive Hoberman Sphere inside a plexiglass box that would mechanically expand, and contract based on audience proximity. Using a motorised linkage system and planned distance sensors embedded in the plinth, the sphere was programmed to display four emotional states—healthy, curious, defensive, and scared—reflecting its stress level as people approached. Although sensor installation was prevented by COVID restrictions, the concept positioned the sphere as a trapped, reactive being, highlighting the impact of human presence on the well-being of other entities.

Desired Impact on Audience

The primary impact is to get the audience to empathise with and understand the character created by the sphere. The installation is intended to demonstrate the impact of human actions on other living things. By making the sphere's movement directly responsive to human actions, the team intended to compel viewers to recognise that when they pay attention, they can do something. The final setup was specifically designed to evoke feelings associated with a caged animal trapped for the pleasure of visitors.

Team 4 – WHELD – End-of-Life Cycle

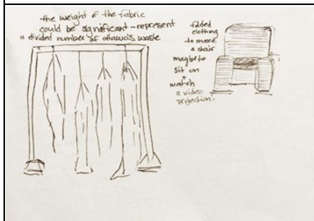
Project Focus

This project, titled "T4 WHELD," explores the end-of-life cycle of consumer objects, specifically using recycled cardboard boxes.

Artistic Statement

The central goal of the work is to address the unsustainability of current production and disposal practices, which require a paradigm shift in thinking. The project aims to start a conversation with the audience about how objects, like cardboard boxes, can be reused and reimagined to restart the product life cycle. The work seeks to give new importance to simple objects by making viewers aware of the effort and energy put into their creation. It pushes the idea that creating a new thing does not always involve production; instead, it asks if rearranging or shifting the value attributed to end-of-life products can be considered a form of creation.

Intermediary Prototypes

Prototype	Description
	P1. Fast Fashion concept discarded.
	P2. The team tested different form options for the projection surface, comparing a uniform arrangement of identical boxes with a layout using varied box sizes. While consistent sizes offered a clean, predictable canvas, the mixed-size approach introduced unexpected edges and hidden pockets that created a more dynamic visual experience and encouraged viewers to engage more actively with the installation.
	P3. Focused on content themes such as abstracted ideas of production, reuse, and product life cycles. Tested themes included manufacturing production cycles, biological cycles, raw materials, and objects changing state (melting, freezing, etc.).
 Video Link	Artifact 1. The final prototype transitioned to a digital format due to campus closures, shifting from a planned physical installation with projection mapping to a fully virtual experience. The project featured manipulated manufacturing-process videos—reversed, sped up, or partially keyed out—to obscure their sequence and prompt viewers to rethink how such processes could be improved. By revealing the cardboard box structure beneath the visuals and developing a 3D model for future interactive use, the design aimed to immerse users in critically examining production systems.
 Website Link	Artifact 2. The final solution included a 3D model of the boxes to give the user a feeling of being part of the process. The team hoped to develop a website where the user could click on a video to randomly change it from a list, mimicking the idea of altering or rethinking the manufacturing lifecycle.

Desired Impact on Audience

The project is designed to compel the viewer to rediscover the beauty of simple objects and judge their relationship with end-of-life products. The core impact is instilling a questioning mentality regarding product life cycles. By viewing manipulated processes, the audience is motivated to develop a more analytical perspective of production cycles, leading them to alter the way they look at consumption for the better. Ultimately, the project aims for action and self-realisation within the consumer economy, urging viewers to rethink processes and change how they consume.

Team 5 – Power Arrangers– The Surveillance Tree

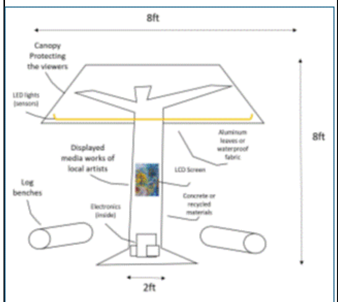
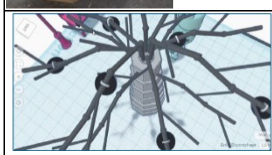
Project Focus

The project "**Surveillance Tree**" realised by the Power Arrangers team, centred on exploring urban environments and their impact on mental well-being, specifically through the theme of hostile urban design and surveillance.

Artistic Statement

The Surveillance Tree explores the theme of hostile urban environments, drawing attention to the role that both architecture and public video surveillance play in creating uncomfortable public spaces. The team wished to comment on the nefarious and insidious psychological impact that public surveillance has on city dwellers, which marks them as potential suspects and creates an overall atmosphere of suspicion and distrust. The tree motif, which usually symbolises life, wisdom, and connection, is used ironically to contrast those ideas with the "twisted idea of connection via global surveillance networks".

Intermediary Prototypes`

<table>
<tr><th>Prototype</th><th>Description</th></tr>
<tr><td>
</td><td>P1. The first prototype explored an outdoor gallery concept featuring a tree-shaped sculpture with LCD screens displaying local artwork and seating beneath for community interaction. While visually engaging, feedback showed that attention would shift toward the displayed art rather than the sculptural intervention itself, and the concept was deemed too broad to meaningfully address the urban environment or align with Situationist themes.</td></tr>
<tr><td></td><td>P2. The second prototype, the Surveillance Tree, shifted focus to modern urban issues such as hostile architecture and constant monitoring by replacing fruit with security cameras on a concrete-like tree structure. A proof-of-concept model was built using plywood, cardboard, and real security cameras to demonstrate the intended full-scale installation. The concept was well received, with recommendations to include a live camera feed and additional branches to enhance its critical commentary on surveillance culture.</td></tr>
<tr><td></td><td>Artifact 1 (view 1). The Surveillance Tree exaggerates the harsh aesthetic of modern architecture with concrete-coated blocks and sharp rebar branches, while its dangling security cameras—described as the “fruit” of the tree—mockingly reinforce the constant paranoia and vulnerability created by urban surveillance.</td></tr>
<tr><td></td><td>Artifact 1 (View 2). The final prototype of the Surveillance Tree could not be physically completed due to COVID-19 campus closures, but the intended design featured a full-scale concrete-like tree made from stacked hollow plywood octagons, rebar branches, and faux security cameras to evoke the harshness of surveillance culture. To demonstrate the concept, the team produced a detailed virtual model in TinkerCad along with a construction demo video, conveying the planned 9 ft x 8 ft installation and its critical commentary on hostile urban environments.</td></tr>
</table>

Desired Impact on Audience

The primary aim of the venture is to challenge the trends of hostile design in the public landscape by making a statement regarding the deviation of urban development toward increasingly unwelcoming features. The exaggerated architectural and technological elements are meant to draw attention to the psychological impact that surveillance has on city dwellers, who are made to feel uneasy and anxious in public spaces. The imposing structure is intended to act as a "defiantly disagreeable inanimate opponent".

APPENDIX S Iteration 6 Artifacts Collected

Team 1 – Fast Fashion and Wast SDG-12

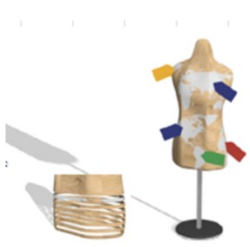
Project Focus

The project involved three distinct prototypes leading to a final artistic visualisation piece focusing on the issue of fast fashion and waste, aligning with Sustainable Development Goal (SDG) 12.

Artistic Statement

The artistic visualisation piece addresses the critical sustainability issue of fast fashion and waste, aligning with SDG 12, which focuses on sustainable consumption and production patterns. The core message is to convey the extensive environmental harm that has been caused by the overconsumption of fashion products. The video delivers key facts and statistics conveying the urgency of SDG 12. Through the video, the team hoped to convey that avoiding participating in the rapid cycling of trends and treating clothes as disposable can slow down the detrimental effects of fast fashion.

Intermediary Prototypes and Conceptual Designs

Prototype	Description
	P1. Mannequin Bust (Conceptual Design) The initial concept was a sculpture based on a mannequin bust. This prototype was envisioned as an interactive mannequin upon which pieces of data would be imposed. Specific features included QR Code Price tags, a Laser Cut Structure with overlaid fabric, and a World Map made of fabrics. The team eventually realised this visualisation did not seem like the best vehicle to communicate their purpose, as they struggled to fit their story into the physical piece.
	P2. Textile Wave (Conceptual Design) This prototype transitioned the concept to a digital format using Powtoon to create a whiteboard animation. While this stage had a manageable time frame, the result was an Uncomplete story. This shift was made after assessing other prototypes and receiving peer feedback, as the whiteboard animation concept enabled the team to effectively illustrate their message, data, and storyline in a timely manner.

 	P3. Storyboard
	Artifact. Final Artifact is a whiteboard animation created using Powtoon. The team found that the whiteboard animation format allowed them to deliver key facts and statistics and convey the urgency of SDG 12.

Desired impact on the audience:

The primary goal is to incite viewers to reevaluate their consumption practices. The team believes the video successfully presents a compelling story that incites the audience to evaluate their own consumption habits. The broader purpose is that urging people to reevaluate their clothing consumption practices could potentially encourage them to change the way they consume other goods as well, thereby addressing the overarching goal of SDG 12—ensuring sustainable consumption and production patterns. To maximise impact, a key future step is to circulate the video on social media channels (especially YouTube) to boost viewership and reach, ensuring the story spreads widely.

Team 2 - Dark Side of Fast Fashion – SDG 12

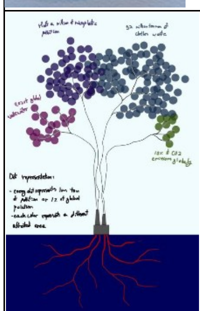
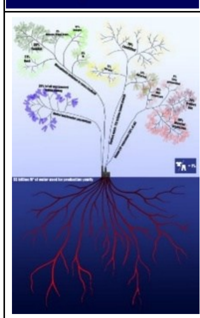
Project Focus

The project aimed to create an artistic visualisation addressing the negative environmental impact of fast fashion and waste, aligning with Sustainable Development Goal (SDG) 12: Responsible consumption and production.

Artistic Statement

The visualisation focuses on exploring the "dark side of fast fashion". The core message is to reveal how the industry depletes natural resources while contributing to environmental pollution. The goal was to convey the extensive environmental harm caused by the overconsumption of fashion products. By linking the resource consumption and the environmental impacts, the team intended to suggest that fast fashion is not a cost-effective industry and that action is time for everyone to act. The visualisation was designed to look "beautiful at the first glance" but encourage viewers to reflect on the "darkness behind such beauty".

Intermediary Prototypes and Conceptual Designs

Prototype	Description
	P1. Conceptual Design Before the first prototype, the team explored several visualisation sketches, including designs based on a cycle, plants, marine life, and a tree. The team chose to evolve the tree sketch because it offered flexibility to represent multiple impacts of fast fashion on the environment.
	P2. The second prototype refined the initial pollution concept by combining the earlier sea and tree sketches into a more polished visual metaphor. Data was represented through color-coded garments—T-shirts and pants—showing human involvement in pollution, while roots symbolised the excessive water consumption fueling the fashion industry's environmental impact. By structuring information across branches and using colors to distinguish different pollutant sources, the design aimed to reveal the "illusion of beauty" in fashion while exposing its hidden ecological costs.
	Artifact. The final artifact is an appealing and informative illustration of a tree created using Adobe Photoshop. The team focused on refining the aesthetic quality and clarifying the data representation. Changes included: Unifying the size of the clothes (T-shirts and pants) to avoid confusion; Making the text bolder and bigger; Adding a legend to assist with the interpretation of the visual elements; Making the root section bigger and more impactful, including text explaining that it represents the consumption of resources.

Desired Impact on Audience

The primary desired impact is to raise the awareness of every customer and encourage them to reflect on their purchases on clothes. The project aims to circulate the final visualisation widely. The team has planned to publish the illustration on various platforms, including social media, commercial boards in shopping centres (like Rideau Centre), and boards at the University of Ottawa, to reach a big audience and increase awareness of fast fashion's negative environmental impacts.

Team 3 – Amit's Storybook about India`s Forests – SDG 13

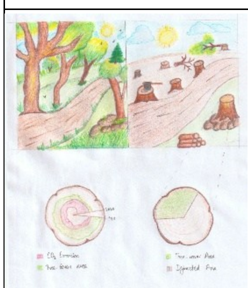
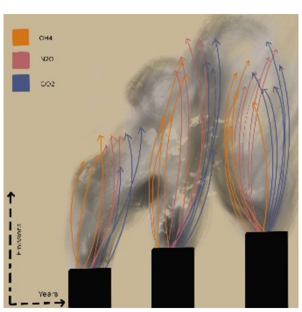
Project Focus

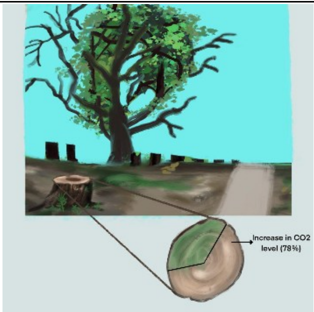
This project focuses on addressing Sustainable Development Goal (SDG) 13: Climate Action, specifically concentrating on reducing carbon dioxide emissions and preserving forests in India. The final deliverable is a children's storybook.

Artistic Statement

The book's goal is to present climate change and climate action in a palatable way for younger audiences (6 to 11 years old). The artistic visualisation aims to show a contrast between what Amit pictured the world to be and what it is right now by creatively showing data on the images. The underlying message is that the world has enough resources to satisfy everyone's needs, but not everyone's greed, as quoted by Mahatma Gandhi. The book teaches the audience about the causes and effects of climate change and encourages them to take action to restore nature.

Intermediary Prototypes and Conceptual Designs

Prototype	Description
	P1. The initial prototype centred on deforestation in India and introduced the story of a young boy comparing the natural world of the past to the damaged environment of the present. Though broad in scope, the early visuals—such as tree rings representing data—established the foundation for the direction of the project. This stage led to the development of a storyboard to refine the narrative and guide the evolution of the final design.
	P2. The second prototype significantly refined the concept by narrowing the focus to the impact of mass deforestation on land levels in India and shifting the format from an e-poster to an informational children's book. Using Procreate for digital illustration, the team developed scenes featuring Amit and his grandmother alongside contrasting visuals of the land in the past versus the present, while also improving the clarity of emissions and environmental data in the narrative.



Artifact. The final artifact is a 17-page illustrated children’s book titled Amit’s Story, following a young boy in India who contrasts his grandmother’s memories of the environment with the current impacts of climate change. Through embedded data visualisations—such as tree rings showing deforestation—the book teaches readers about environmental challenges and highlights solutions for a more sustainable future.

Desired Impact on Audience

The core desired impact is to educate the audience on the effects of deforestation and empower them to participate in the movement to fight climate change. The team hopes that ‘Amit’s story’ will be published so it can reach and teach its audience effectively. A potential future enhancement suggested was to include a packet of seeds along with the storybook so readers could actively participate in fighting deforestation by planting them. The project encourages individuals to implement small sustainable choices, such as recycling or using public transport.

Team 4 – The Shadow Pandemic – SDG 3

Project Focus

This project focuses on addressing the increase of domestic violence against women (VAW) due to the COVID-19 pandemic, often referred to as "The Shadow Pandemic," aligning with Sustainable Development Goal (SDG) 3: Good Health and Wellbeing.

Artistic Statement/Message

The visualisation addresses the theme that domestic violence happens behind closed doors. The central artistic goal was to combine hard data with human experiences to produce an artistic concept that palates the collected facts. Using abstraction, the team focused on the essence of the problem: domestic violence across the globe, COVID-19, and the change in rates during that time. The resulting comic strip seeks to reveal the shocking violence against women.

Intermediary Prototypes and Conceptual Designs

Prototype	Description
	P1. The initial concept used honeybees as a metaphor for tourism, visualising countries as flowers and flights as bees transferring pollen to represent global travel. However, the idea was rejected because the data on COVID-19's impact on tourism was already widely known, and the metaphor lacked strong logical and conceptual grounding for the project's goals.
	P2. The intermediary prototype shifted focus to domestic violence, using an apartment view where buildings represented countries, barred windows indicated rising rates of violence against women, and changing skies showed the passage of time. Despite its strong intent to link violence, poverty, food insecurity, and COVID-19 impacts, the concept was eventually discarded due to unreliable data, visual overcrowding, and difficulty effectively conveying the narrative.
	Artifacts 1&2. The final artifacts merged data and human experience through two main visual components. Artifact 1. First, an interactive Tableau world map displayed UN and WHO statistics on violence against women before and during COVID-19, enabling viewers to explore the data by country. This approach provided a clear, fact-based foundation for understanding the global scale of the issue.

	Artifact 2. Second a storybook followed a character named Sandra as she revealed the hidden violence affecting women around her, helping humanise the statistical data through a relatable narrative. An animated presentation accompanied both elements, tying the data visualisation and storytelling together for the final Design Day pitch.

Desired Impact on Audience

The project aims to raise awareness about violence against women by combining clear data with a compelling personal narrative. Partnering with the University of Ottawa Women's Resource Centre and seeking support from the Human Rights Office, the team plans to launch a student-focused campaign and expand to other organisations. By evolving from a complex data concept to a simple yet powerful mix of an interactive map and a relatable comic story, the project highlights that confronting the shadow pandemic requires both solid statistics and the human stories behind them.

APPENDIX T Iteration 7 Artifacts Collected

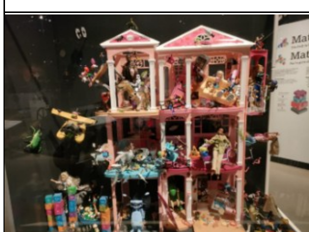
Team 1 - Barbie

Project Focus

The project focused on the past and future of Barbie, exploring her influence on society and addressing the problem of plastic waste generated by the toy.

Artistic Statement: The artistic intent behind Future Barbie addressed both the environmental impact of plastic dolls and the stereotypes associated with Barbie's image by aligning the redesign with UN SDGs on gender equality, sustainable innovation, and responsible consumption. The prototype aimed to retain Barbie's iconic beauty while redefining her as a symbol of environmental responsibility and empowerment.

Intermediary Prototypes

Prototype	Description
	Artifact Chosen. This was the initial visual focus, inspired by an unconventional dollhouse display at the Canada Science and Technology Museum – Ingenium. The dollhouse was unorganised, mixing various Barbies and toys, and was displayed to explain plastic compositions and the resources used to create plastics. Act 1 focused on the whole picture behind Barbie and her influence in society.
	P1. This phase focused on Barbie herself and the cultural and political influences present during her creation in the 1960s. It highlighted both **gender and racial equality**.
	Artifact. The final artifact, **Future Barbie**, was a one-meter sustainable toy constructed from bio-based, reusable, and recyclable materials such as moss, garbage bags, cellophane, and repurposed newspaper featuring gender equality headlines. Designed to align with UN Sustainable Development goals, the doll aimed to raise awareness of environmental responsibility and women's rights while showcasing how toys can be reimagined using diverse eco-friendly materials.

Desired Impact on Audience:

Future Barbie aimed to transform the iconic doll into a powerful symbol of sustainability and gender equality by integrating recycled and bio-based materials while challenging stereotypes tied to her image. By aligning the design with key UN SDGs and enlarging the prototype to draw attention, the project highlighted how toys can reduce plastic waste and simultaneously serve as platforms for promoting women's rights and global sustainability issues.

Team 2 - Biomimic Octo-Suit

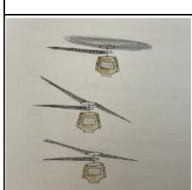
Project Focus

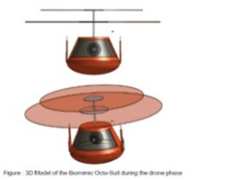
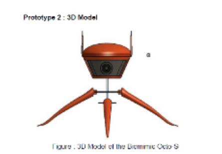
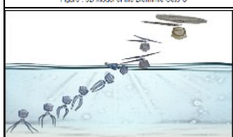
The project focused on redesigning a deep-sea diving suit replica, selected from the Ingenium collection, into a futuristic and sustainable artifact called the *Biomimic Octo-Suit*.

Artistic Statement

The artistic intent behind the Biomimic Octo-Suit was guided by the UN Sustainable Development Goals and a commitment to minimising human interference in nature. The design reimagines a diving suit as a sustainable, autonomous system built with durable materials that reduce resource use while enabling vital underwater research, conservation, and pollution prevention through advanced monitoring technologies.

Intermediary Prototypes Description

Prototype	Description
	Original Artifact The project focused on redesigning a deep-sea diving suit replica, selected from the Ingenium collection, into a futuristic and sustainable artifact called the Biomimic Octo-Suit.
	P1. This was the first prototyping phase where the initial concept was introduced. A sketch was created to establish the basic features of the robot, specifically its ability to transition between underwater deployment and flight above water. This sketch was presented to the class and professors for initial feedback.

	P2. Prototype 2 involved creating a more detailed visual representation using a 3D model. The model was built using CAD software Onshape and Blender. This allowed the team to visually define the concept and create all the physical components of the robot. This prototype was viewed in virtual reality using Oculus. Feedback on this prototype suggested adding grabbing fingers to the tentacles for improved discovery experience.
	P3. The final prototype, the Biomimic Octo-Suit, is a small autonomous robot designed for deep-sea exploration without the need for human divers. It features a hybrid system that allows it to operate underwater and then transition into a drone to return independently to its base, with remote human guidance when needed.
	P3. By removing traditional diving suit elements like oxygen tanks, it becomes more sustainable and capable of longer missions. Its durable exterior is made from a pressure-resistant composite, supported by a titanium-alloy exoskeleton, and equipped with sensors, AI-powered maneuverability, internal heating, and a compact hydrogen-cell energy system for advanced performance.

(Note: the team wished they had enough time to make a real physical prototype, but they created a 3D model to better visualise and represent the complex concept.)

Desired Impact on Audience:

The project aimed to create an immersive experience that brought its ideas to life while encouraging audiences to rethink humanity's relationship with the ocean. By blending technology, sustainability, and storytelling, the team sought to inspire environmental action, highlight the role of innovative design in protecting ecosystems, and demonstrate how complex ideas—like the UN SDGs—can be made engaging and accessible.

Team 4 – Portable Hair Dryer

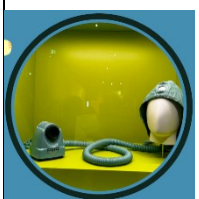
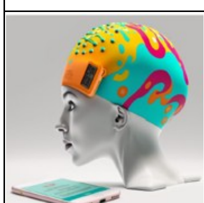
Project Focus

This project centred on the redesign of a 1950s Vintage Sunbeam Hair and Nail Dryer from the Ingenium museum collection. The goal was to transform this artifact into an innovative, sustainable, portable, and cordless bonnet hair dryer, aligning with modern technological standards and sustainability goals.

Artistic Statement/Central Theme:

The project reimagined the vintage artifact through a sustainability lens, aligning the design with the UN SDGs—particularly Goal 9 on sustainable innovation. The aim was to create an energy-efficient, portable hair dryer that appeals to confident, independent women seeking both practicality and environmental responsibility, while remaining market-viable.

Intermediary Prototypes Description

Prototype	Description
	Artifact Initial. Inspired by the vintage look, this prototype aimed for portability and sustainability. It featured a bonnet connected via a hose to a separate cordless hair dryer. The material planned for the redesign included silicon and recycled plastics. Challenges included concerns about the necessity of the bonnet if users could just use the cordless dryer, and difficulties in ensuring efficient heat distribution through the hose.
	P1. Developed in ACT 3, this design eliminated the need for a separate cordless hair dryer and the connecting hose. Instead, battery power and fans were integrated into the bonnet itself, providing a hands-free experience. This design incorporated a portable power bank (27000mAh/100W capacity) and internal fans, inspired by neck dryers, to improve heat distribution and reduce drying time. Challenges included the added weight of the power bank and ensuring sufficient battery life for thorough drying.
	Artifact Final. The final artifact improved weight and efficiency by replacing the bulky power bank with a compact Maxon EC45 motor and a lightweight energy 12V rechargeable battery. This portable system delivers efficient, variable-speed performance while retaining sustainable materials, resulting in a cordless, eco-friendly bonnet hair dryer.

Desired Impact on Audience:

The redesigned hair dryer aims to significantly improve user experience while reducing environmental impact. Its cordless, portable design increases freedom of movement, making it easier to use while multitasking, traveling, or after activities like swimming. By incorporating rechargeable batteries and exploring options like USB or solar charging, the prototype also reduces reliance on single-use batteries and lowers waste. Ultimately, the project demonstrates how innovative, sustainability-focused design can contribute to a greener future and inspire more responsible consumer products.

Team 5 - Nostalgia

Project Focus

The project focused on selecting and transforming the Polyphon music box from the 1900s into a futuristic, sustainable artifact called "Nostalgia". The redesign adhered to sustainable design practices and aligned with the United Nations' Sustainable Development Goals (SDGs).

Artistic Statement

The project advanced sustainability by aligning with key UN SDGs, reducing reliance on non-renewable materials like wood (SDG 15) and reimagining the device as a tool for emotional well-being and social connection in a dystopian future. By evoking comforting memories and reinforcing shared identity, the Nostalgia Box supports both mental health (SDG 3) and community cohesion (SDG 16).

Intermediary Prototypes (Design Evolution)

Prototype	Description
	Artifact Initial. The initial artifact was selected for its intriguing form and potential to synthesise multiple instruments. This stage included a formal object analysis and embodied storytelling, which increased the team's appreciation for the complexity of seemingly simple objects.
	P1: The initial prototype was a transparent, sustainably constructed box designed with a slit to insert a picture, serving as the structural foundation for the device. At this early stage, it focused solely on exploring the physical form and materials, without yet incorporating the technical or functional components planned for later iterations

	P2. The team used DALL·E to generate design ideas, resulting in an image featuring a transparent cylindrical form atop a square base with visible musical notes. This simple yet refined aesthetic helped inspire the visual direction of the final prototype.
	Artifact Final. The final Artifact called the Nostalgia Box, was conceived as a sustainable music player for a dystopian future, capable of scanning a physical photograph and generating music that matches its mood. Built from recycled plastic and glass using 3D printing and laser cutting, the transparent design revealed its inner workings while incorporating inclusive elements like braille and branded visual cues. Although technical constraints limited full functionality, the interactive concept was demonstrated through a supporting web app that simulated the image-recognition and music-selection process.

Desired Impact on Audience:

The sustainable Polyphon aimed to inspire environmentally conscious design by showcasing the use of recycled and biodegradable materials while fostering emotional connection in a disconnected future through music linked to physical photographs. By incorporating braille and emphasising tactile interaction, the project highlighted accessibility and the value of physical experiences as pathways to memory and meaning.

Team 6 – Laser Harp

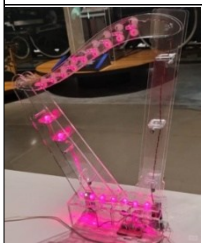
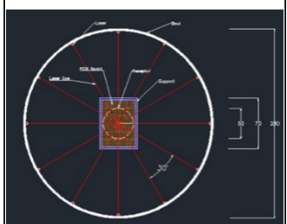
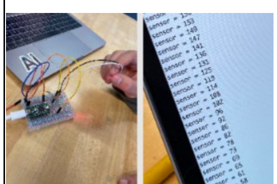
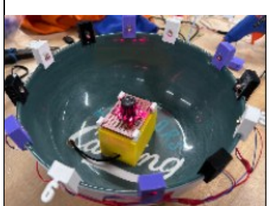
Project Focus

This project focused on re-imagining the *laser harp* displayed at Ingenium, transforming it into a more accessible and sustainable *Laser Bowl Instrument*.

Artistic Statement

The artistic vision behind the Laser Bowl Instrument centred on sustainability and reducing waste in the music industry by replacing short-lifespan physical components with long-lasting lasers and multifunctional electronic design. By supporting UN SDG 12 on responsible consumption, the instrument minimises material use, eliminates tuning and mechanical maintenance, and introduces an innovative clock-based notation system that reduces the need for multiple instruments while offering a fresh way to connect music with time and space

Intermediary Prototypes (Design Evolution)

Prototype/Phase	Description
	Artifact Initial. The initial artifact was selected for its intriguing form and potential to synthesise multiple instruments. This stage included a formal object analysis and embodied storytelling, which increased the team's appreciation for the complexity of seemingly simple objects.
	P1: The team agreed to redesign the laser harp, which they believed had a lot of potential. The initial plan was to create a laser instrument with the potential for synthesising multiple instruments, but the form was unknown. The team decided to use a **closed frame** for simplicity. This stage also involved analysing the sustainability of the laser instrument compared to traditional instruments.
	P2. This phase involved creating a functional proof-of-concept using one laser. Key technical steps included soldering the electronics, programming the teensy board, and prototyping 3D printed components. The team created the first **prototypal 3D printed components**, and visuals show testing of the sensor readings based on blocking the laser. The team agreed on the **bowl structure** at this point.
	Artifact Final. The final artifact, the **Laser Bowl Instrument**, reimagined the original vertical laser harp into a bowl-shaped design to enhance accessibility and sustainability. Lasers were repositioned along the rim to project toward a central receptor, with a Teensy board translating notes into a clock-based system. The instrument maintains eco-friendly advantages such as long-lasting laser "strings" and the potential for modular combination with other instruments, while text-to-image AI supported visual exploration of the laser-based performance experience.

Desired Impact on Audience

The Laser Bowl Instrument aimed to showcase the sustainability benefits of laser-based music by reducing waste compared to traditional materials while enhancing performance through visually immersive laser effects. By integrating multiple functions into one durable form and challenging conventional instrument design, the project encouraged audiences to rethink what musical technology can be and how it can contribute to a more sustainable future.

Team 7 – Salamander Suit

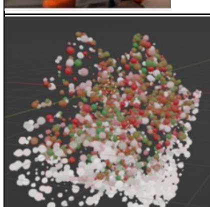
Project Focus

This project reimagined the 1300-pound Newtsuit as a sustainable, near-future diving technology aligned with UN SDGs—particularly Goal 9 (Industry, Innovation & Infrastructure) and Goal 14 (Life Below Water). The redesign aimed to significantly reduce the environmental impact of current manufacturing practices, especially the high emissions associated with aluminum production.

Artistic Statement/Central Theme:

The artistic concept centred on reducing the carbon footprint of the original diving suit by replacing environmentally damaging aluminum with sustainable materials. Guided by themes of innovation, feasibility, and ocean protection, the design incorporated eco-friendly components like Yulex rubber and energy-converting elements to support marine conservation while presenting a realistic near-future solution.

Intermediary Prototypes (Design Evolution)

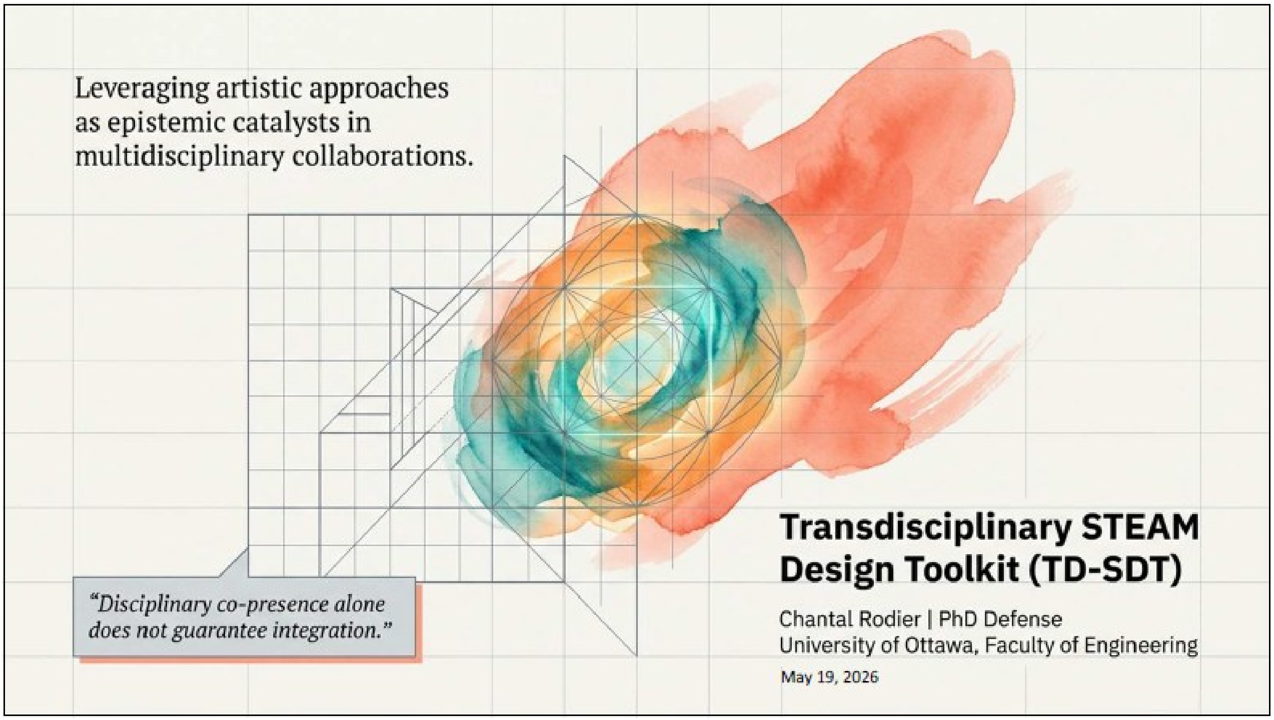
Prototype	Description
	Original Artifact The project focused on redesigning a deep-sea diving suit replica, selected from the Ingenium collection, into a futuristic and sustainable artifact.
	P.1 Prototype 1 explored underwater survival in a warming world, imagining an evolved suit inspired by marine life and powered by eco-friendly, energy-converting fabrics—reflecting a future where materials themselves support sustainability and life.
	P.2 This phase expanded the theme of energy-recycling eco-friendly fabrics by integrating a system of carbon-fixing microorganisms, seashell-based clean energy sources, and gene-editing concepts inspired by sea urchins to highlight sustainability and the interconnectedness of humans and marine life.

	Artifact Final. The final “salamander suit” artifact was designed as a sustainable, near-future diving suit, using Yulex natural rubber reinforced with aluminum alloy to withstand harsh conditions. It featured a rebreather system that recycles exhaled air for extended dive times and was visualised through 3D modeling and VR to demonstrate its innovative potential.

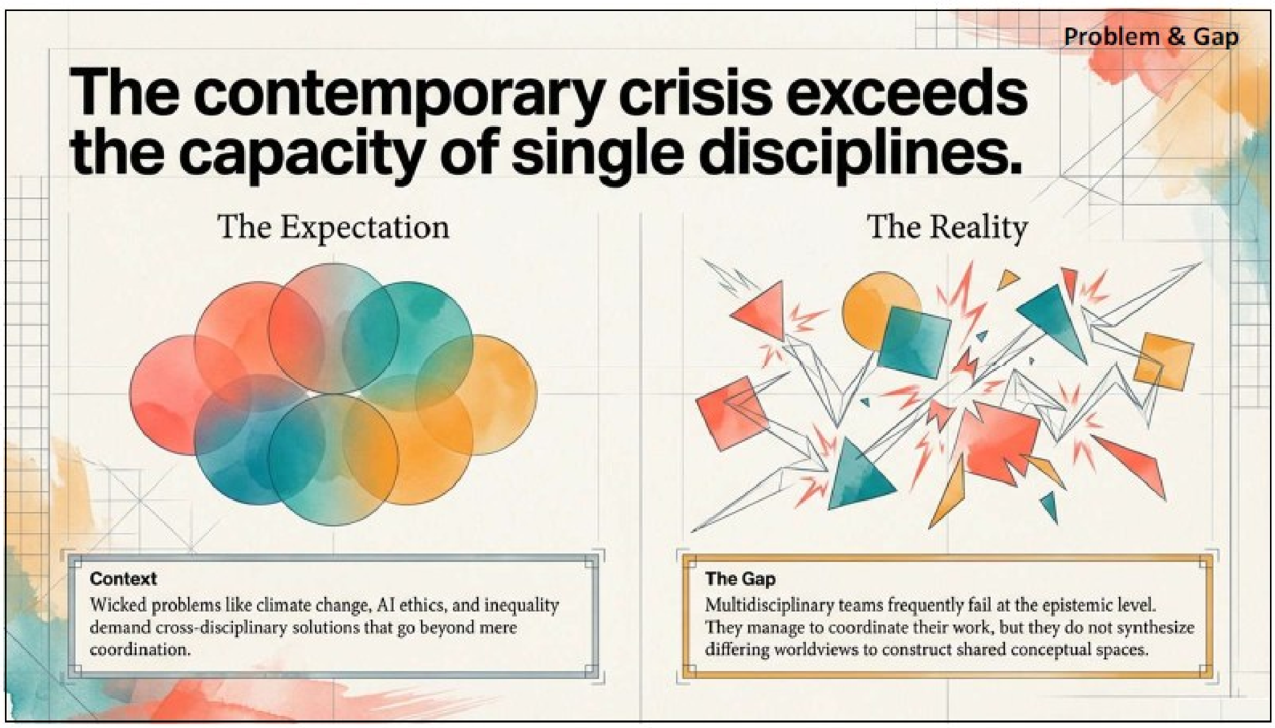
Desired Impact on Audience:

The sustainable suit was designed to raise environmental awareness by highlighting the impacts of traditional materials like aluminum while demonstrating how innovative alternatives such as Yulex rubber and rebreather technology can support longer-lasting, eco-friendly solutions. The team emphasised empathy by encouraging audiences to consider both user needs and the historical context of the original suit, while also inspiring future innovation—imagining a world where underwater exploration drives new sustainable discoveries.

APPENDIX U Research Presentation



1



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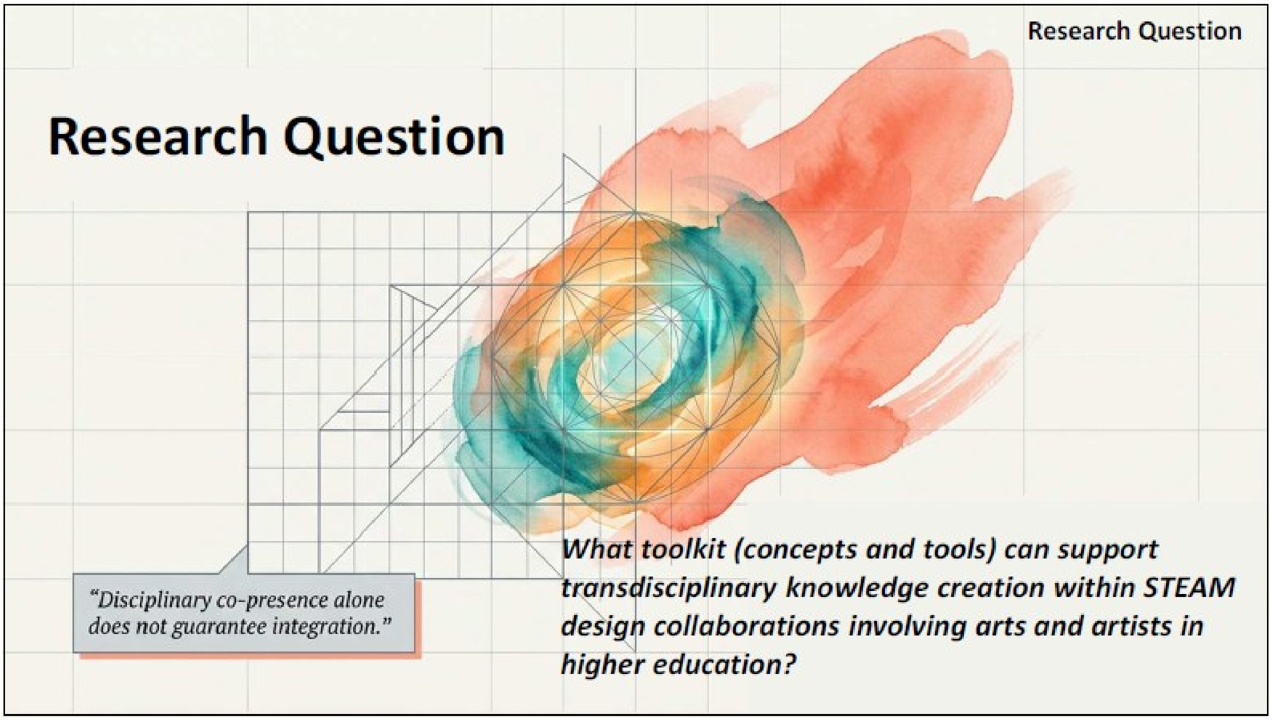
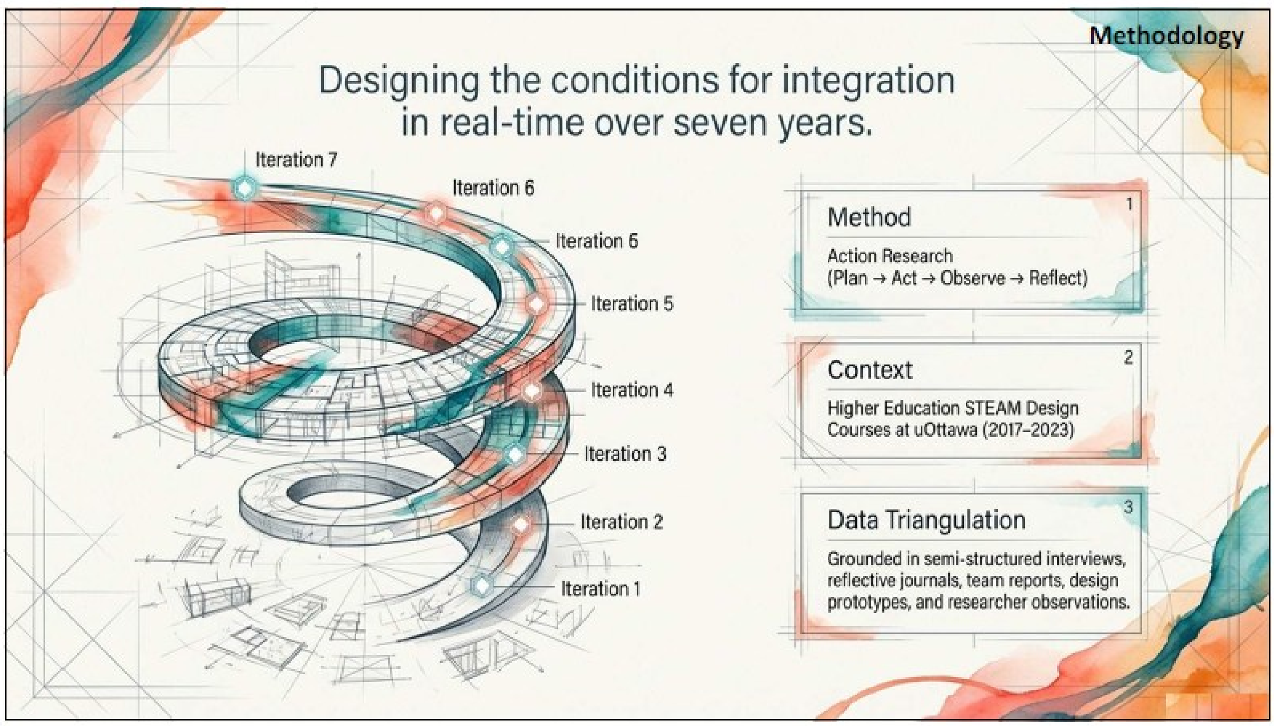
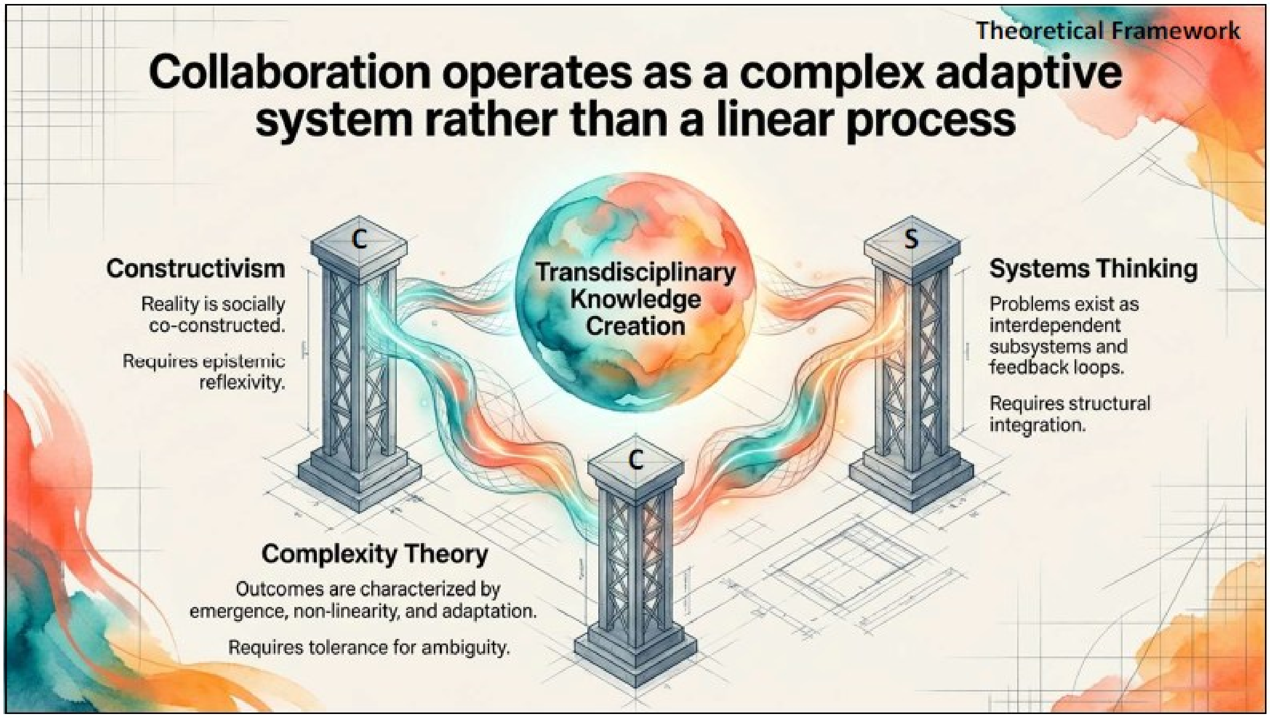

Research Question
Research Question
"Disciplinary co-presence alone does not guarantee integration."
What toolkit (concepts and tools) can support transdisciplinary knowledge creation within STEAM design collaborations involving arts and artists in higher education?

3


Methodology
Designing the conditions for integration in real-time over seven years.
Iteration 7
Iteration 6
Iteration 6
Iteration 5
Iteration 4
Iteration 3
Iteration 2
Iteration 1
Method
1
Action Research
(Plan → Act → Observe → Reflect)
Context
2
Higher Education STEAM Design Courses at uOttawa (2017–2023)
Data Triangulation
3
Grounded in semi-structured interviews, reflective journals, team reports, design prototypes, and researcher observations.

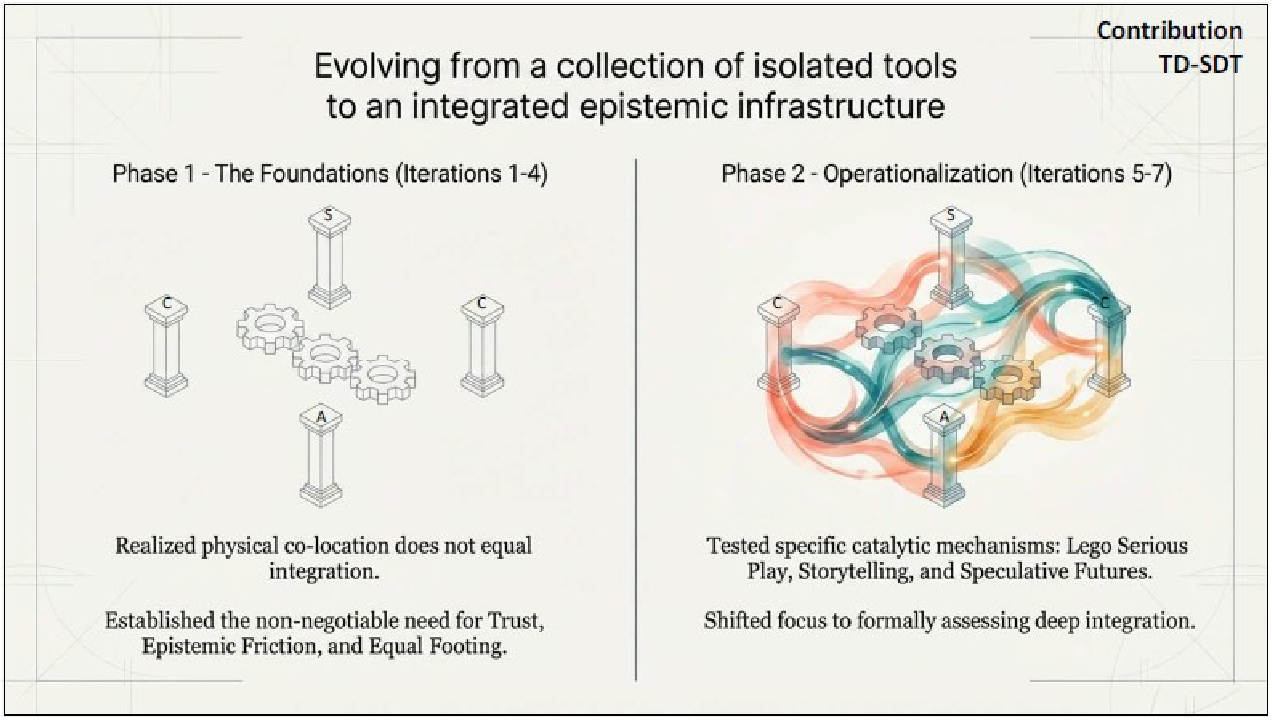
4


Theoretical Framework
Collaboration operates as a complex adaptive system rather than a linear process
C
Constructivism
Reality is socially co-constructed.
Requires epistemic reflexivity.
Transdisciplinary Knowledge Creation
S
Systems Thinking
Problems exist as interdependent subsystems and feedback loops.
Requires structural integration.
C
Complexity Theory
Outcomes are characterized by emergence, non-linearity, and adaptation.
Requires tolerance for ambiguity.

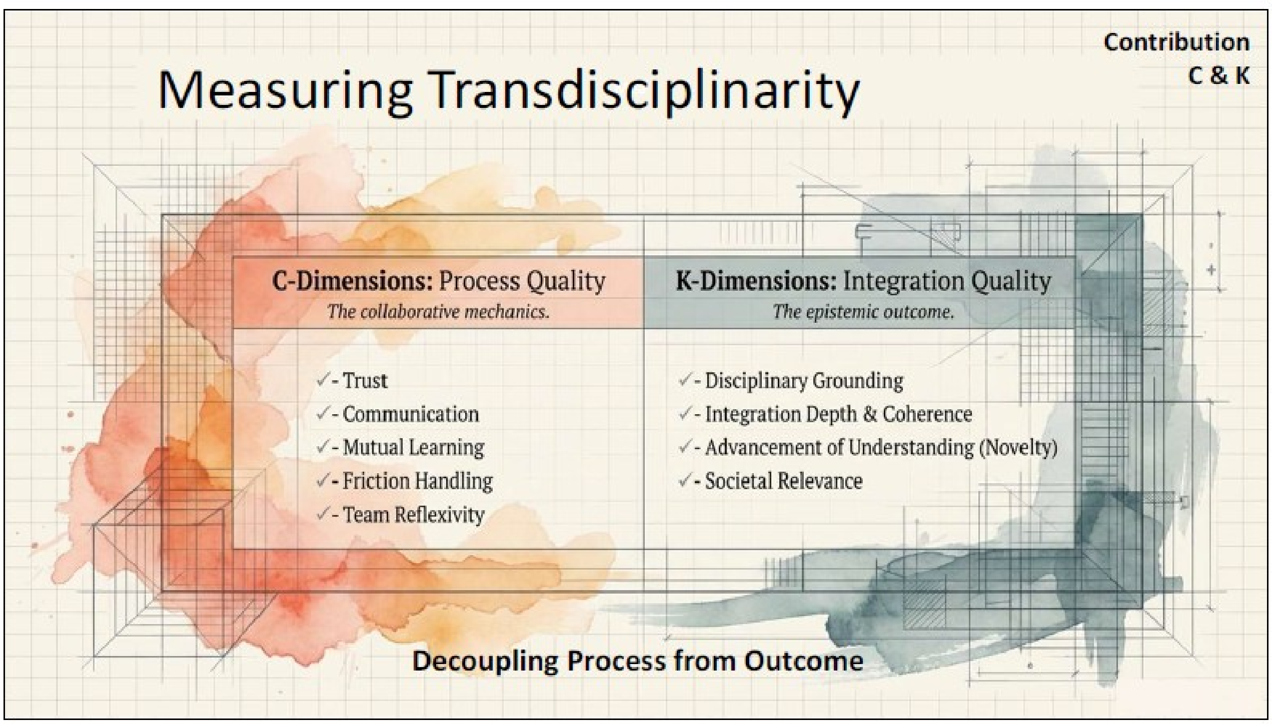
5


Theoretical Framework
Arts Build
Epistemic & Onthological Capacity
Redefining the A in STEAM:
Art is not supplementary; it is an active epistemic and ontological agent.
Foundational
Offering Creative Problem Solving,
Humanising Complex Issues,
Fostering Emotional and Psychological Resilience
Epistemic & Ontological
Functioning as Epistemic and Ontological Agents
Cultivating Tolerance for Ambiguity
Deepening Ethical Reflection
Generating Transdisciplinary Knowledge
Systemic
Building Shared Futures,
Enabling Behavioural Change
Contributing to Symbolic Infrastructure

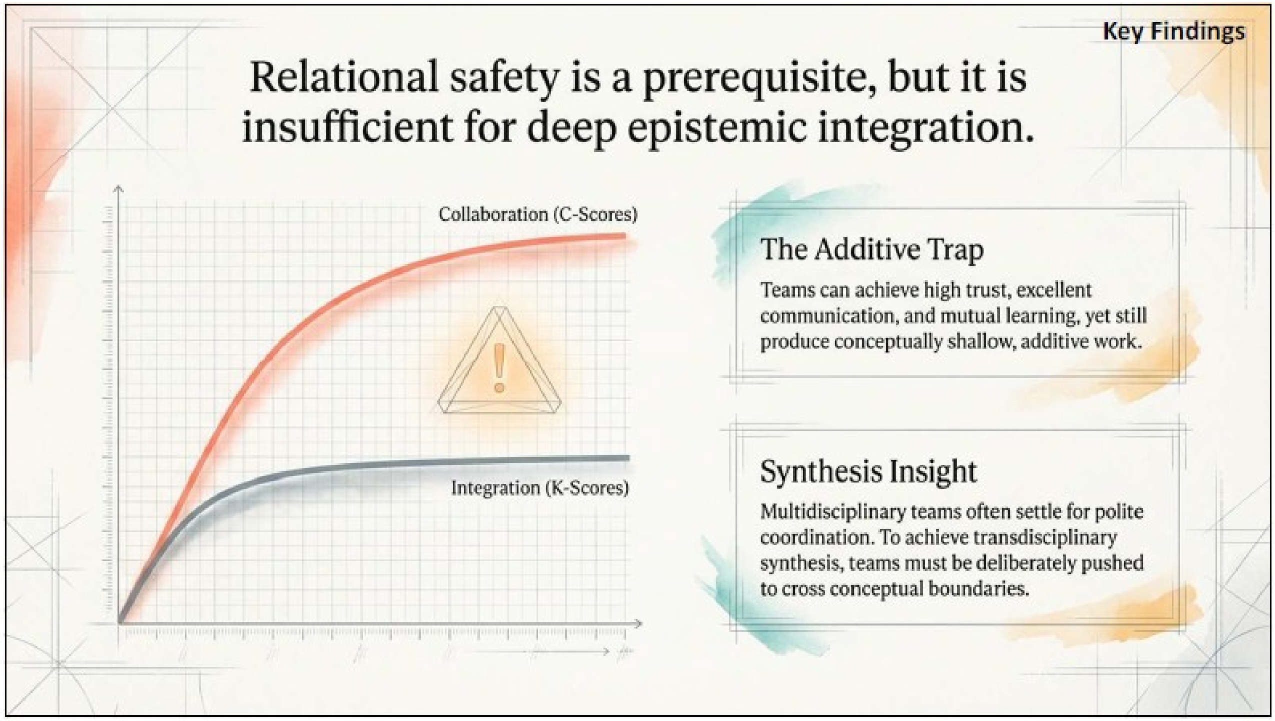
6


Contribution
TD-SDT
Evolving from a collection of isolated tools to an integrated epistemic infrastructure
Phase 1 - The Foundations (Iterations 1-4)
Phase 2 - Operationalization (Iterations 5-7)
S
C
C
A
S
C
C
A
Realized physical co-location does not equal integration.
Established the non-negotiable need for Trust, Epistemic Friction, and Equal Footing.
Tested specific catalytic mechanisms: Lego Serious Play, Storytelling, and Speculative Futures.
Shifted focus to formally assessing deep integration.

7


Contribution
C & K
Measuring Transdisciplinarity
C-Dimensions: Process Quality
The collaborative mechanics.
✓- Trust
✓- Communication
✓- Mutual Learning
✓- Friction Handling
✓- Team Reflexivity
K-Dimensions: Integration Quality
The epistemic outcome.
✓- Disciplinary Grounding
✓- Integration Depth & Coherence
✓- Advancement of Understanding (Novelty)
✓- Societal Relevance
Decoupling Process from Outcome

8


Key Findings
Relational safety is a prerequisite, but it is insufficient for deep epistemic integration.
Collaboration (C-Scores)
Integration (K-Scores)
The Additive Trap
Teams can achieve high trust, excellent communication, and mutual learning, yet still produce conceptually shallow, additive work.
Synthesis Insight
Multidisciplinary teams often settle for polite coordination. To achieve transdisciplinary synthesis, teams must be deliberately pushed to cross conceptual boundaries.

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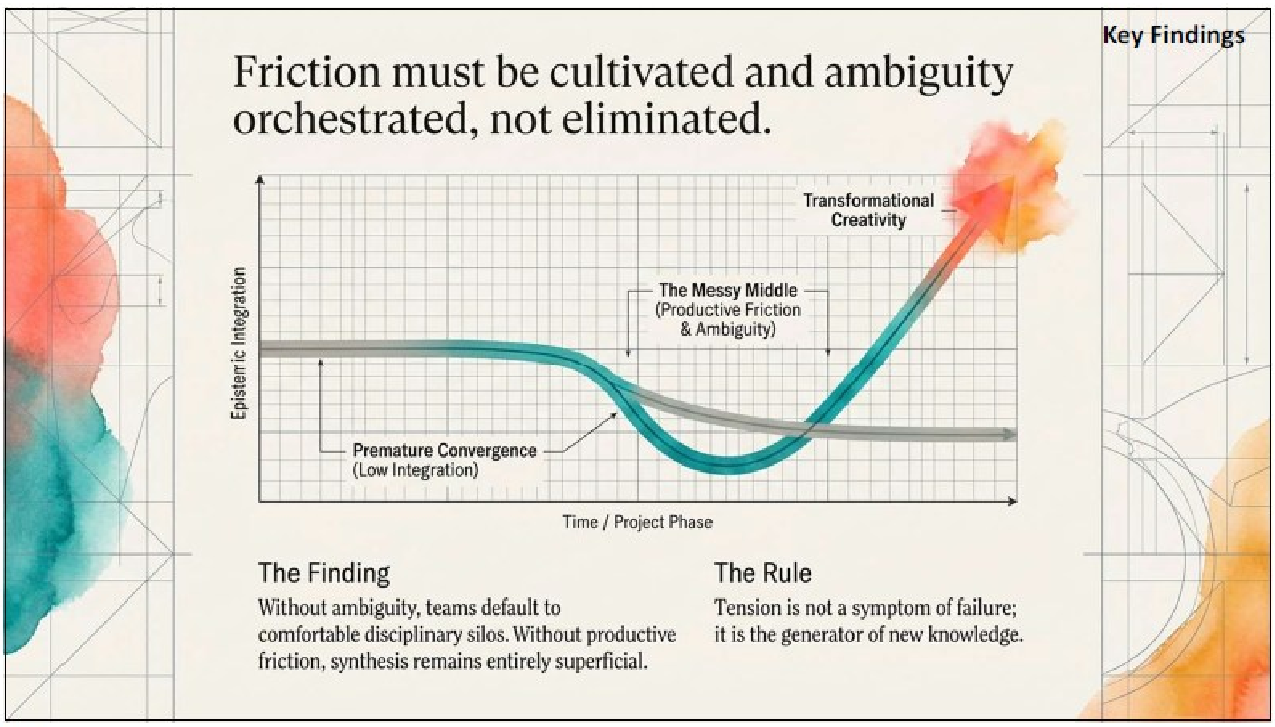
Key Findings
Friction must be cultivated and ambiguity orchestrated, not eliminated.
Transformational Creativity
The Messy Middle (Productive Friction & Ambiguity)
Epistemic Integration
Premature Convergence (Low Integration)
Time / Project Phase
The Finding
Without ambiguity, teams default to comfortable disciplinary silos. Without productive friction, synthesis remains entirely superficial.
The Rule
Tension is not a symptom of failure; it is the generator of new knowledge.

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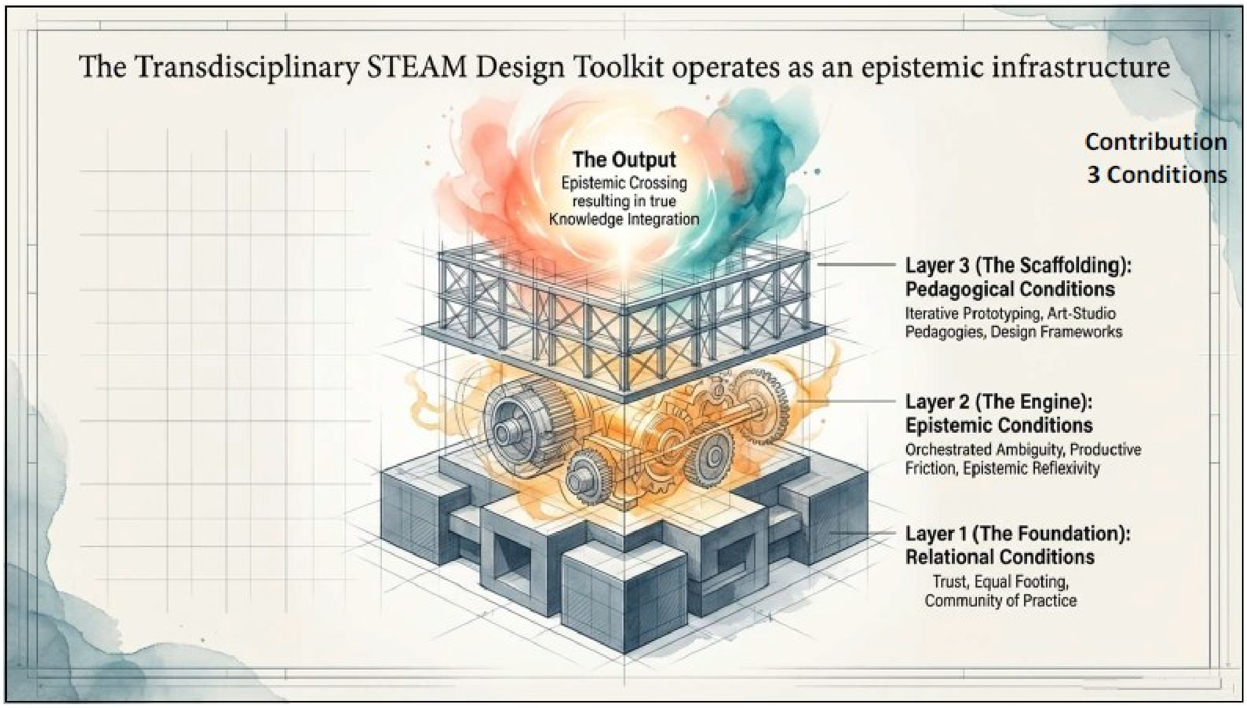
The Transdisciplinary STEAM Design Toolkit operates as an epistemic infrastructure
Contribution
3 Conditions
The Output
Epistemic Crossing resulting in true Knowledge Integration
Layer 3 (The Scaffolding):
Pedagogical Conditions
Iterative Prototyping, Art-Studio Pedagogies, Design Frameworks
Layer 2 (The Engine):
Epistemic Conditions
Orchestrated Ambiguity, Productive Friction, Epistemic Reflexivity
Layer 1 (The Foundation):
Relational Conditions
Trust, Equal Footing, Community of Practice

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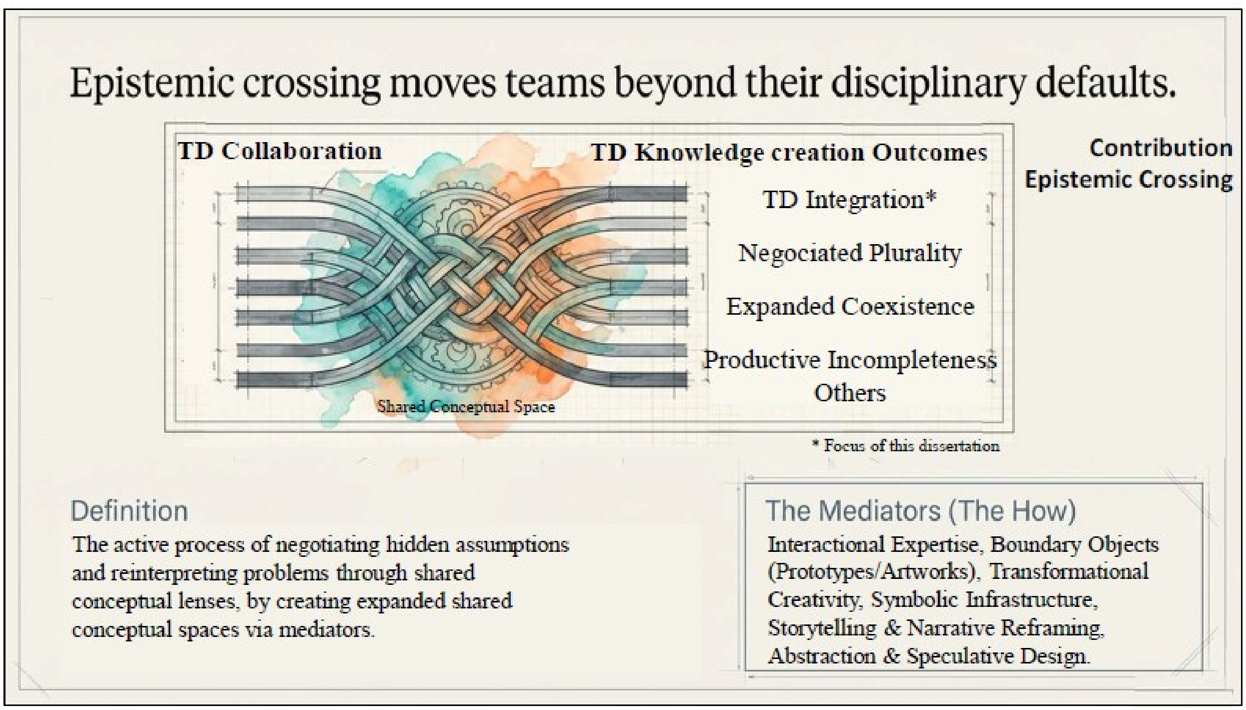
Epistemic crossing moves teams beyond their disciplinary defaults.
Contribution
Epistemic Crossing
TD Collaboration
TD Knowledge creation Outcomes
TD Integration*
Negociated Plurality
Expanded Coexistence
Productive Incompleteness
Others
Shared Conceptual Space
* Focus of this dissertation
Definition
The active process of negotiating hidden assumptions and reinterpreting problems through shared conceptual lenses, by creating expanded shared conceptual spaces via mediators.
The Mediators (The How)
Interactional Expertise, Boundary Objects (Prototypes/Artworks), Transformational Creativity, Symbolic Infrastructure, Storytelling & Narrative Reframing, Abstraction & Speculative Design.

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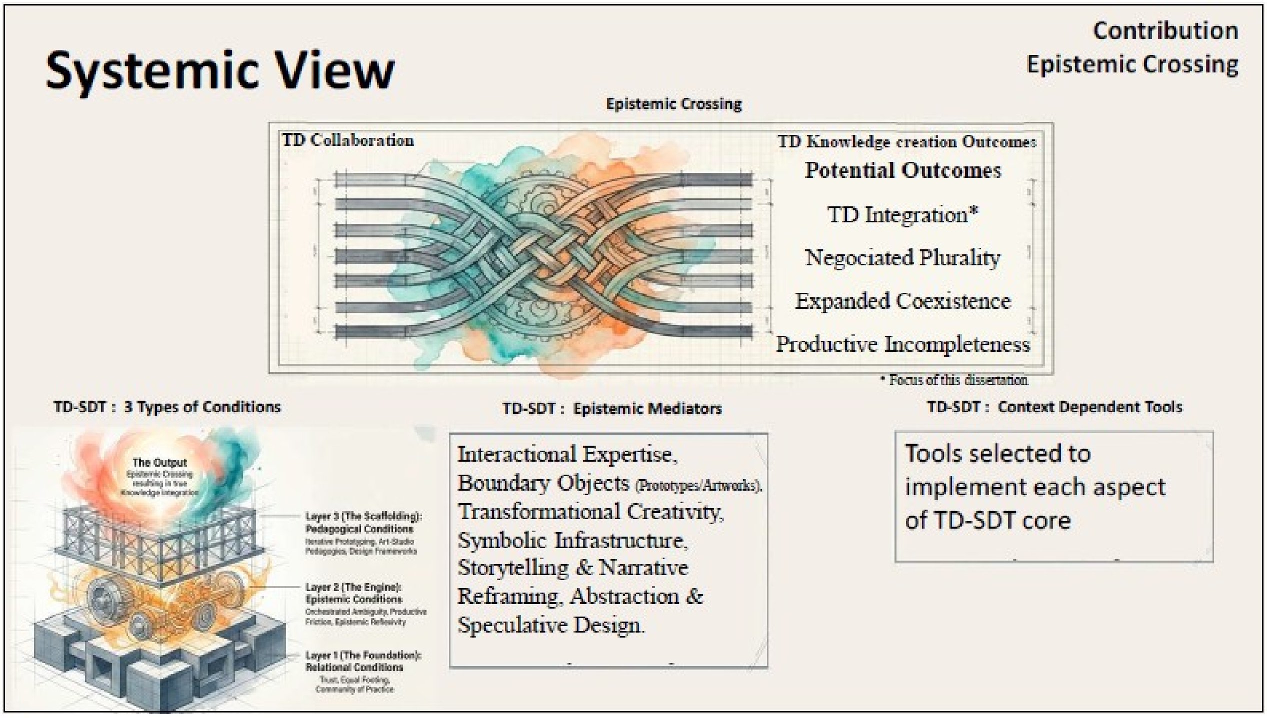
Systemic View
Contribution
Epistemic Crossing
Epistemic Crossing
TD Collaboration
TD Knowledge creation Outcomes
Potential Outcomes
TD Integration*
Negociated Plurality
Expanded Coexistence
Productive Incompleteness
* Focus of this dissertation
TD-SDT : 3 Types of Conditions
The Output
Epistemic Crossing
resulting in true
Knowledge Integration
Layer 3 (The Scaffolding):
Pedagogical Conditions
Iterative Prototyping, Art-Studio
Pedagogies, Design Frameworks
Layer 2 (The Engine):
Epistemic Conditions
Orchestrated Ambiguity, Productive
Friction, Epistemic Reflexivity
Layer 1 (The Foundation):
Relational Conditions
Trust, Equal Footing,
Community of Practice
TD-SDT : Epistemic Mediators
Interactional Expertise,
Boundary Objects (Prototypes/Artworks),
Transformational Creativity,
Symbolic Infrastructure,
Storytelling & Narrative
Reframing, Abstraction &
Speculative Design.
TD-SDT : Context Dependent Tools
Tools selected to
implement each aspect
of TD-SDT core

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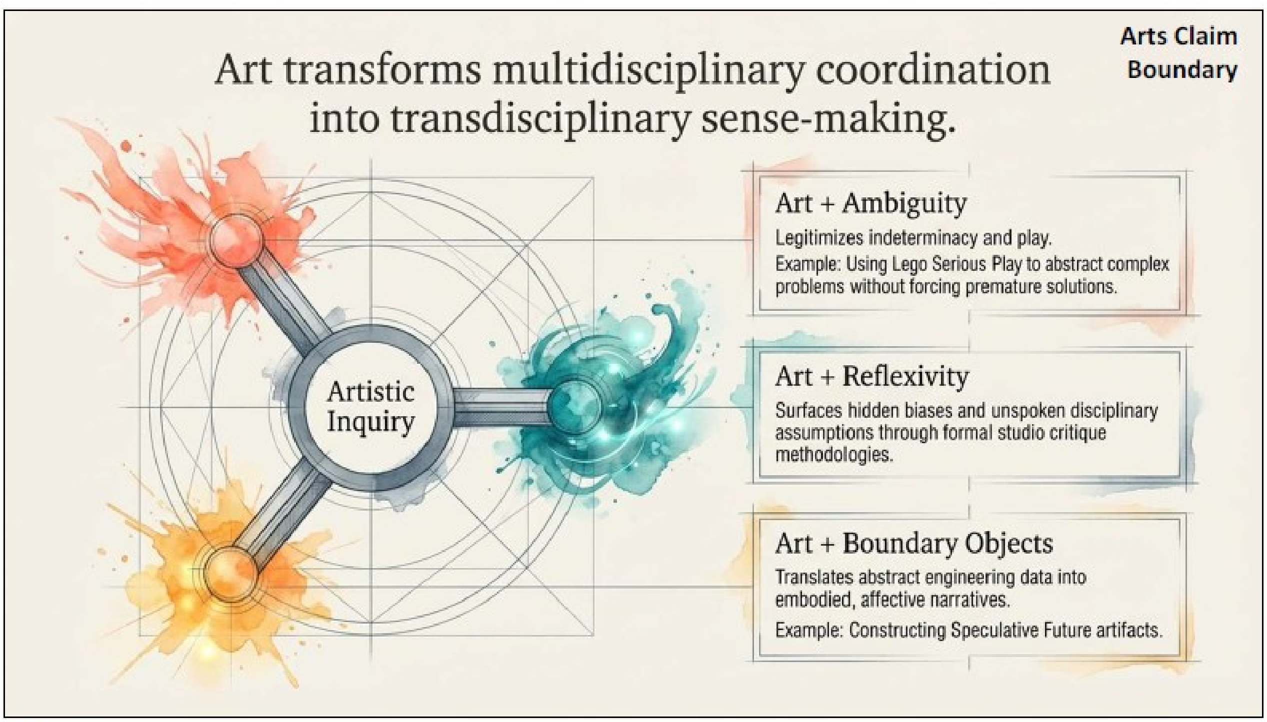
Arts Claim
Boundary
Art transforms multidisciplinary coordination
into transdisciplinary sense-making.
Artistic
Inquiry
Art + Ambiguity
Legitimizes indeterminacy and play.
Example: Using Lego Serious Play to abstract complex
problems without forcing premature solutions.
Art + Reflexivity
Surfaces hidden biases and unspoken disciplinary
assumptions through formal studio critique
methodologies.
Art + Boundary Objects
Translates abstract engineering data into
embodied, affective narratives.
Example: Constructing Speculative Future artifacts.

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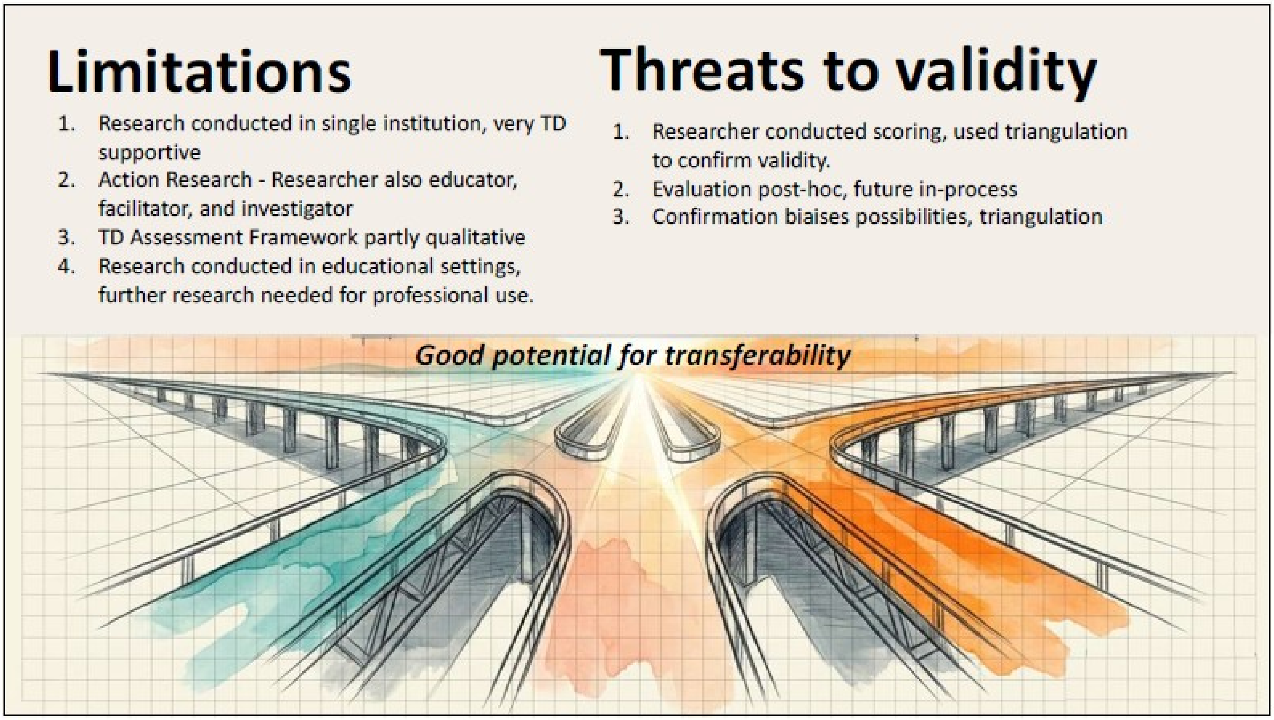
Limitations
1. Research conducted in single institution, very TD supportive
2. Action Research - Researcher also educator, facilitator, and investigator
3. TD Assessment Framework partly qualitative
4. Research conducted in educational settings, further research needed for professional use.
Threats to validity
1. Researcher conducted scoring, used triangulation to confirm validity.
2. Evaluation post-hoc, future in-process
3. Confirmation biaises possibilities, triangulation
Good potential for transferability

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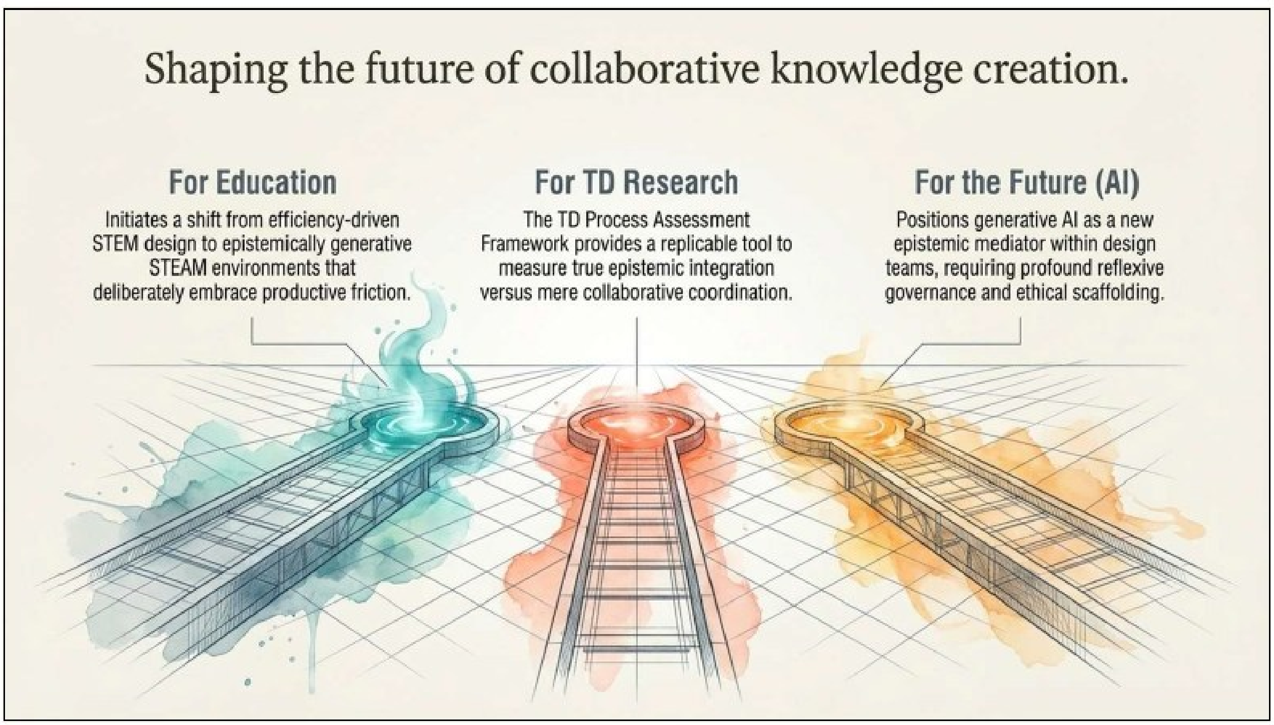
Shaping the future of collaborative knowledge creation.
For Education
Initiates a shift from efficiency-driven STEM design to epistemically generative STEAM environments that deliberately embrace productive friction.
For TD Research
The TD Process Assessment Framework provides a replicable tool to measure true epistemic integration versus mere collaborative coordination.
For the Future (AI)
Positions generative AI as a new epistemic mediator within design teams, requiring profound reflexive governance and ethical scaffolding.

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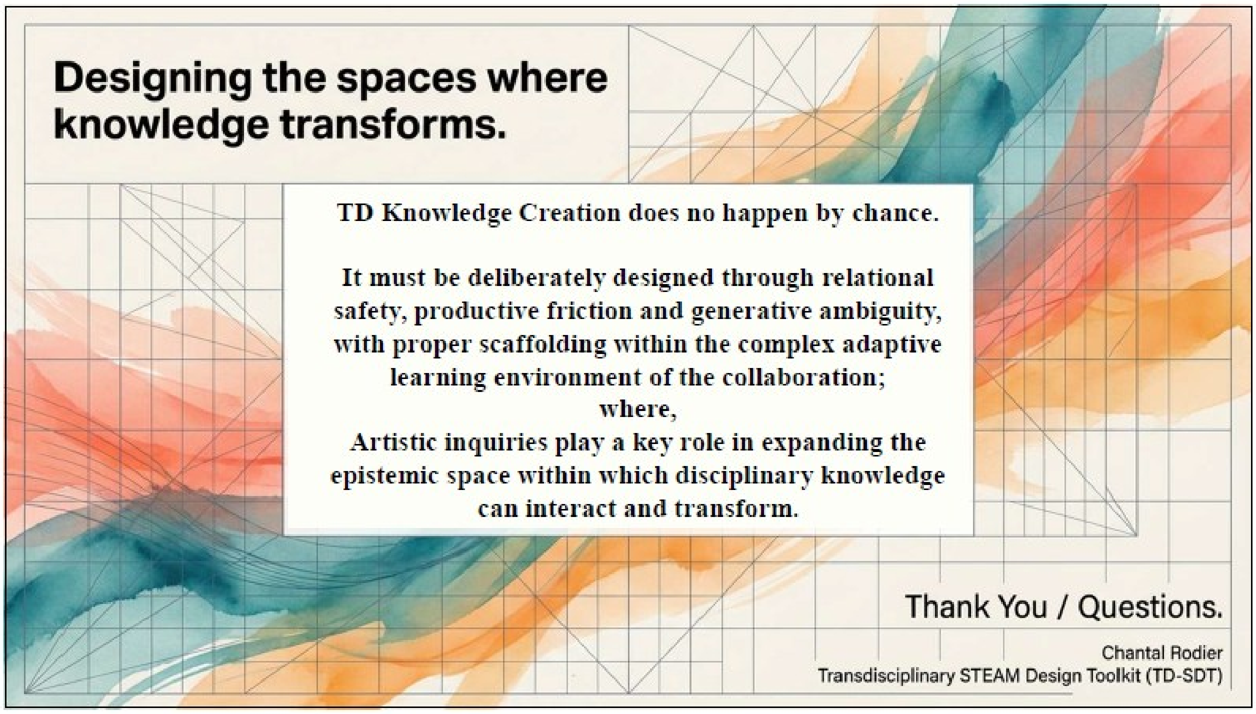
Designing the spaces where knowledge transforms.
TD Knowledge Creation does no happen by chance.
It must be deliberately designed through relational safety, productive friction and generative ambiguity, with proper scaffolding within the complex adaptive learning environment of the collaboration;
where,
Artistic inquiries play a key role in expanding the epistemic space within which disciplinary knowledge can interact and transform.
Thank You / Questions.
Chantal Rodier
Transdisciplinary STEAM Design Toolkit (TD-SDT)

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