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Transdisciplinary Innovation

Welcome to the August issue of the *Technology Innovation Management Review*. We welcome your comments on the articles in this issue as well as suggestions for future article topics and issue themes.

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Overview

The *Technology Innovation Management Review* (TIM Review) provides insights about the issues and emerging trends relevant to launching and growing technology businesses. The TIM Review focuses on the theories, strategies, and tools that help small and large technology companies succeed.

Our readers are looking for practical ideas they can apply within their own organizations. The TIM Review brings together diverse viewpoints – from academics, entrepreneurs, companies of all sizes, the public sector, the community sector, and others – to bridge the gap between theory and practice. In particular, we focus on the topics of technology and global entrepreneurship in small and large companies.

We welcome input from readers into upcoming themes. Please visit timreview.ca to suggest themes and nominate authors and guest editors.

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About TIM

The TIM Review has international contributors and readers, and it is published in association with the Technology Innovation Management program (TIM; timprogram.ca), an international graduate program at Carleton University in Ottawa, Canada.

Editorial: Transdisciplinary Innovation

Chris McPhee, Editor-in-Chief

Martin Bliemel and Mieke van der Bijl-Brouwer, Guest Editors

From the Editor-in-Chief

Welcome to the August 2018 issue of the *Technology Innovation Management Review*. This month's editorial theme is **Transdisciplinary Innovation**, and it is my pleasure to introduce our Guest Editors, **Martin Bliemel** and **Mieke van der Bijl-Brouwer**, who are both from the Faculty of Transdisciplinary Innovation at the University of Technology Sydney, Australia.

Looking ahead to a related future issue, please note the upcoming special issue on **Action Research** with guest editors **Magnus Hoppe** (the author of the first article in this issue) and **Erik Lindhult** from Mälardalen University in Sweden. The submission deadline for abstracts is October 1, 2018. Please see the call for papers for details: tinyurl.com/yd5gacsv

For other future issues, we are accepting general submissions of articles on technology entrepreneurship, innovation management, and other topics relevant to launching and growing technology companies and solving practical problems in emerging domains. Please contact us (timreview.ca/contact) with potential article topics and submissions, and proposals for future special issues.

Finally, we invite you to attend ISPIM Connects Ottawa (ispim-connects-ottawa.com), which will be held in Ottawa, Canada, from April 7–10, 2019. The TIM Review and its associated academic program at Carleton University, the TIM Program (timprogram.ca), are proud to be the local hosts of the event in collaboration with other partners.

Chris McPhee
Editor-in-Chief

From the Guest Editors

We are living in a rapidly changing, hyper-connected world and are facing increasingly global, complex, and dynamic problem situations such as income disparity, environmental crises, organized crime, and health management issues. These complex or "wicked" problems cannot be adequately tackled from the sphere of individual disciplines, because they are not individual problems, they are interrelated and "intrinsically linked in a meta-system of problems", and as such cannot be solved in isolation (Rittel et al., 1973; Özbekhan, 1970: 13). Complex problem situations require what has been defined as a *trans*disciplinary approach (Jantsch, 1972). There are many definitions of transdisciplinary innovation and transdisciplinary research, but a general consensus is that transdisciplinary innovation has the following characteristics: it is action-oriented and future-focused, participatory, holistic and systemic, and purposive, and it transcends individual disciplines or practices (Jantsch, 1972; Klein, 2002; Polk, 2015).

A transdisciplinary approach to innovation differs from multidisciplinary and interdisciplinary approaches in that it is not just about working towards a shared goal or having disciplines interact with and enrich each other (Figure 1). Instead, transdisciplinary innovation is about placing these interactions in an integrated system with a social purpose, resulting in a continuously evolving and adapting practice (van der Bijl-Brouwer, 2018). A by-product of transdisciplinary innovation is that the integrated solution contributes back to the disciplines it drew upon to evolve them, too.

The term "transdisciplinarity" was originally coined and developed within academia as a response to the fragmented organization of universities into faculties, schools, and degrees. More recently, transdisciplinarity is increasingly relevant to innovators and entrepreneurs whose technologies or solutions are aimed at addressing complex societal problems. This larger-scale emphasis moves innovation beyond "customer-centred" to a "society-centred" perspective, and it requires active collaboration with public and private sector organizations, governments, and communities.

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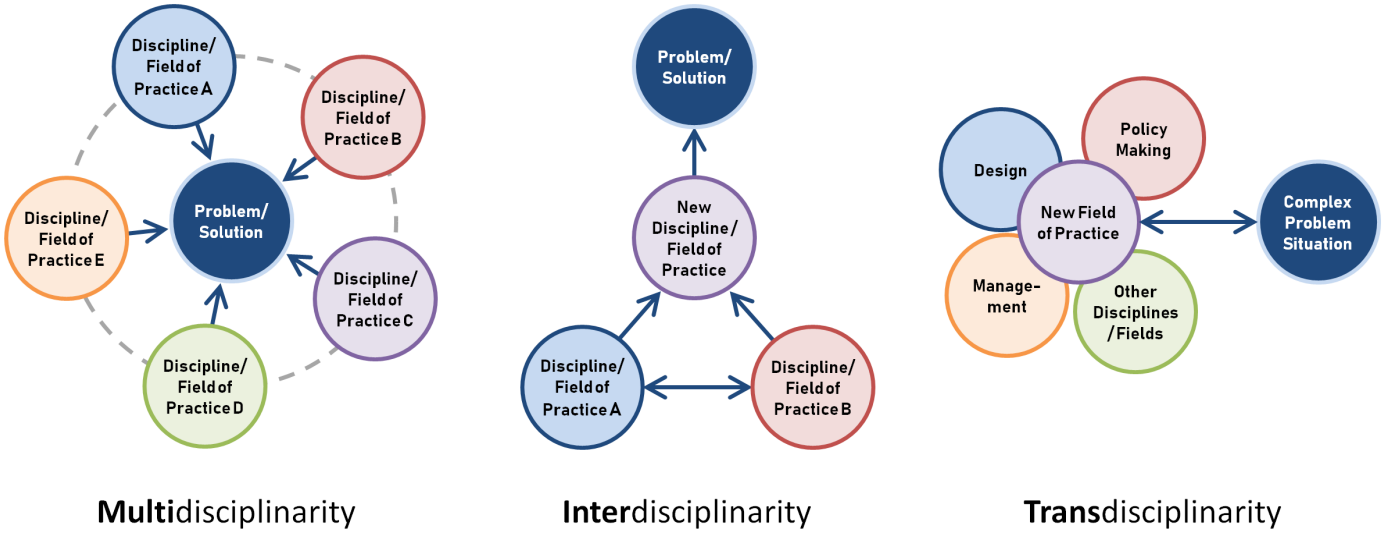

Figure 1. A comparison of multidisciplinary, interdisciplinary, and transdisciplinary approaches to innovation

This special issue includes a rich and nuanced set of takeaways for practitioners, academics, and members of the public or third sectors. We highlight four of them here, regarding learning, spaces, levels of impact, and partner selection. We nonetheless strongly encourage you to read the entire set of articles to make sure you get a balanced overview of different ways in which transdisciplinary innovation occurs.

Key takeaways of this special issue:

1. The first of the overarching takeaways recognizes that transdisciplinary innovation is more than coordinated input from multiple knowledge domains to solve a problem (see Figure 1: Multidisciplinarity). With transdisciplinary innovation, solving the problem results in new knowledge forming via the integration of those domains that contributes back to them (see Figure 1: Transdisciplinarity, noting the two-way arrow). In other words, learning is an inherent part of transdisciplinary innovation. This learning can occur by individual innovators (see Zafeirakopoulos and van der Bijl-Brouwer in this issue) or as a collective (see Riedy et al., and Baumber et al., in this issue).

2. The second key takeaway is that the unpredictability of transdisciplinary innovation requires giving it "space" and not over-constraining or controlling it. The articles by Femenías and Thuvander and Riedy and co-authors emphasize this with examples of "space" in the sense of allocating time, physical space, or nurturing interactions between others in a way that does not try to (pre-maturely) force transdisciplinary innovation to progress along a prescribed path.

3. The third takeaway is consideration of what the level of impact of the innovation is. Does it only affect the innovator (often referred to as a transdisciplinary innovation researcher in this special issue)? Or, does it affect the collective group of people directly involved? Or, are the broader social implications of greater importance? Answering these questions can influence how you aim to fund transdisciplinary innovation projects, as exemplified by the projects discussed in the articles by Baumber and co-authors, by McGregor, and by Dorst.

4. The fourth takeaway builds on this by encouraging readers to carefully choose their partners for transdisciplinary innovation projects. This means being conscious of the respective disciplines or practices being integrated as well as being conscious of there being expertise in shepherding the transdisciplinary innovation process. McGregor's article provides an excellent overview of how painstakingly slow transdisciplinary innovation can be if the process is left to emerge organically. Meanwhile, Dorst's article presents an alternative approach in which the integration can be designed into the process at a very early stage.

The first article in this special issue is by **Carolyn McGregor AM**, who draws on her personal decades-long journey of evolving a big data project about neonatal intensive care into astronaut health monitoring. We selected this as the first article in the special issue because it neatly contrasts i) disciplinary innovation occurring in sequence, ii) multidisciplinary innovation occurring as multiple disciplines in parallel,

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and iii) interdisciplinary innovation occurring at the interaction of the knowledge domains. The article concludes with iv) a constructive approach to structure a path for purposeful transdisciplinary innovation in precision public health.

Next, **Alex Baumber**, **Graciela Metternicht**, **Peter Ampt**, **Rebecca Cross**, and **Emily Berry** examine the co-production of online land management tools. This article goes beyond conventional concepts in innovation management that are built on Rogers' adoption of innovation. To do so, this article elaborately presents a case study of transdisciplinary innovation as a participatory development process that integrates perspectives, including those of the end users. But, transdisciplinary innovation is not quite so easy. It simultaneously involves reflexivity, wherein participants challenge assumptions, including their own, thereby learning and developing a more open-minded or transformative approach to co-producing the innovation.

In the third article, **Paula Femenías** and **Liane Thuvander** add further nuance to the management of transdisciplinary innovation by reflecting on 14 years of experience with transdisciplinary research in the built environment. This article highlights the importance of creating a protected or neutral space where transdisciplinary innovation participants can meet as equals to co-produce the innovation. The importance of this space and its sense of ownership is revealed in the authors' humbling insights of how participants expected the facilitators to own or control the space and tell participants what to do, when the facilitators were primarily presenting the opportunity for participants to take ownership of the space. The ability of the facilitators to instil a sense of ownership by all participants is challenged further by the turnover in participants during the transdisciplinary innovation process, with new participants distrusting the facilitator and other participants, plus a general reluctance to take ownership of a project their predecessors started.

In a similar vein, **Chris Riedy**, **Dena Fam**, **Katie Ross**, and **Cynthia Mitchell** of the University of Technology Sydney's Institute for Sustainable Futures (ISF) reflect on long-term experiences with transdisciplinary research. Based on two decades of work aimed at creating change towards sustainable futures, Riedy and co-authors share how they have started to shape learning spaces or "crossroads" within the ISF to facilitate individual and collective learning. They argue that learning is central to transdisciplinary research and practice as it underpins innovation and catalyzes organizational and social change. To nurture individual and collective learning, they acknowledge informal learning opportunities including unplanned conversations, while also actively shaping "formal crossroads" including collective writing, annual retreats – "the centrepiece of transdisciplinary practice" – and roundtable sessions.

In the next article, **Mariana Zafeirakopoulos** and **Mieke van der Bijl-Brouwer** further discuss the concept of learning within transdisciplinary innovation. Where Riedy and co-authors focus on the collective learning experiences of academics, this article is focused on the individual learning experiences of innovation practitioners who have started to shift their originally positivist approach to transdisciplinary ways of working to address complex problems. Based on a series of interviews with innovation professionals, the authors identify the motivations and drivers of practitioners to start and continue transdisciplinary learning, their emotions experienced during the shift, and the dissemination of their new learning into professional practice. These insights help us reflect on intervention points throughout the whole-of-life education journey that practitioners undertake to spark, revive, or amplify the required attitudes that enable innovation.

The first five articles in this special issue highlight the need to bring people together who have different types of knowledge towards transdisciplinary innovation. To complement this view, **Kees Dorst** presents a more strategic approach to address a particular complex problem and to learn from other disciplines. To achieve this, Dorst presents a layered model of "practices", which are the smaller units of action within disciplines. Practices consist of the values we find important, the principles we use to think about them, and the methods and actions we are going to apply. Framing, a design-based practice, is suggested as means to identify practices that can be "mixed" and integrated to innovatively address a particular complex problem. Dorst furthermore proposes to use the layered model for "practice dialogues" between professionals to promote the exchange of practices between disciplines.

We hope that this special issue provides inspiration to "think bigger" and to integrate multiple disciplines and practices on your next projects to the benefit of a larger contingent of society and your own learning. For a more practical toolkit to facilitate cross-disciplinary collaboration, see Griffith, Carruthers, and Bliemel (2018, due in October) for a review or search online for "method

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cards" including ones by our Faculty of Transdisciplinary Innovation (tinyurl.com/ybdkjwnl) at the University of Technology Sydney, Ontario Digital (medium.com/ontariodigital), IDEO (ideo.com), 18f.gov (18f.gsa.gov), and others. Of course, many of the sources mentioned in each article in this special issue are also well worth tracking down to learn more about the philosophy, art, and practice of transdisciplinary innovation.

Martin Bliemel and Mieke van der Bijl-Brouwer
Guest Editors

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About the Editors

Chris McPhee is Editor-in-Chief of the *Technology Innovation Management Review.* Chris holds an MASc degree in Technology Innovation Management from Carleton University in Ottawa, Canada, and BScH and MSc degrees in Biology from Queen's University in Kingston, Canada. He has nearly 20 years of management, design, and content-development experience in Canada and Scotland, primarily in the science, health, and education sectors. As an advisor and editor, he helps entrepreneurs, executives, and researchers develop and express their ideas.

Martin Bliemel is the Director of the Diploma in Innovation at the new Faculty of Transdisciplinary Innovation at the University of Technology Sydney (UTS). Martin holds a BSc (Mechanical Engineering) and MBA from Queen's University in Kingston, Canada, and a PhD in Business from Simon Fraser University in Vancouver, Canada. His research interests include entrepreneurial networks, accelerators, education, research commercialization, entrepreneurial ecosystems, and the entrepreneurial university. His research has been published in several prestigious journals including *Nature Nanotechnology, Entrepreneurship Theory and Practice, Education+Training,* the *International Journal of Entrepreneurial Behavior & Research,* and the *Entrepreneurship Research Journal,* where one of his articles on entrepreneurship education is the journal's most downloaded article. Martin is a recipient of the nationally competitive Office of Learning and Teaching Citation.

Mieke van der Bijl-Brouwer is a Senior Lecturer at the Faculty of Transdisciplinary Innovation at the University of Technology Sydney in Australia. Her research interests span the fields of human-centred design, systemic design, and public and social sector innovation. As a lecturer, she is responsible for coordinating part of the transdisciplinary degree Bachelor of Creative Intelligence and Innovation. Mieke holds a Master of Science degree in Industrial Design Engineering from Delft University of Technology and a PhD on the topic of user-centred design from the University of Twente, both in the Netherlands.

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Keywords: transdisciplinary, transdisciplinarity, innovation, multidisciplinary, interdisciplinary, learning, practice

Using Constructive Research to Structure the Path to Transdisciplinary Innovation and Its Application for Precision Public Health with Big Data Analytics

Carolyn McGregor AM

> *"When scientists are asked what they are working on, their response is seldom 'Finding the origin of the universe' or 'Seeking to cure cancer.' Usually, they will claim to be tackling a very specific problem – a small piece of the jigsaw that builds up the big picture."*
>
> Martin Rees
> Cosmologist and astrophysicist
> Astronomer Royal and Past President of the Royal Society

New approaches to complex societal challenges require a diverse mix of resources and skillsets from different disciplines to create solutions that are of a transdisciplinary innovation nature. The constructive research method enables the purposeful creation of methods, modules, tools, and techniques that have applicability well beyond the case study that motivated their creation. This research presents a bottom-up approach that follows a structured path to transdisciplinary innovation. A method is presented that demonstrates how a set of innovative research collaborations progress from disciplinary innovation to multidisciplinary innovation and ultimately onto interdisciplinary innovation. Anchored in overlapping computer science concepts, drawing on the constructive research methodology for purposeful synthesis and integration between the projects, a greater transdisciplinary goal can emerge. This method is demonstrated through a case study involving a set of big data analytics research projects involving diverse disciplines such as computer science, critical care medicine, aerospace, tactical operations, and public health. The resultant collective vision for transdisciplinary innovation that has resulted offers new approaches to maintaining individual wellness within communities across their entire lifespan on earth and in space.

Introduction

Transdisciplinary research has been described by Pohl (2010) as combinations of four characteristic features of transdisciplinarity: 1) issues of social relevance; 2) transcending beyond and integrating disciplinary paradigms; 3) engaging in participatory research to link abstract and case-specific knowledge; and 4) knowledge unity through synthesis leading to practices that promote common good for the socially relevant issue. This translates to transdisciplinary innovation when goods or services that create value emerge.

One complex societal challenge that has emerged in recent years is that of "precision public health". The term was coined in Australia by Tarun Weeramanthri in 2013 (Dolley, 2018) and is considered to be "a new field driven by technological advances that enable more precise descriptions and analyzes of individuals and population groups, with a view to improving the overall health of populations" (Baynam et al., 2017).

One key technological advance that has emerged as relevant for precision public health is big data analytics. Specifically focused on data with characteristics of volume,

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velocity, and variety, such as data streaming from medical devices, environment sensors, and GPS locators, big data analytics has generated optimism for the potential of its value for health research and interventions (Dolley, 2018). Analytics on big data can be performed at two different stages: 1) in real-time as the streaming data is arriving, known as stream processing, real-time, or online analytics and 2) with persistent historical data after the data has been stored through knowledge discovery or data mining (McGregor, 2013a; Palem, 2014). However, Dolley's (2018) review demonstrates several isolated examples of multidisciplinary and interdisciplinary research and innovation with big data analytics in health that have not been able to evolve to transdisciplinary research and innovation to more broadly create value for precision public health. A systematic approach is required to transcend beyond and integrate disciplinary paradigms to enable the broader impact.

Two research methods are used extensively in the creation or application of new computing and information technology approaches for use in differing domains: constructive research and action research. The constructive research method is a systematic approach that enables the purposeful creation of methods, modules, tools, and techniques that have applicability well beyond the case study that motivated their creation. It is a research paradigm widely used in computer science, mathematics, operations analysis, and clinical medicine (Kasanen et al., 1993). The focus is on the construction, with theoretical demonstration as well as practical implementations as valid outcomes of the research process. Action research, as the name suggests, involves taking action, evaluation, and critical reflection (Koshy et al., 2011). Within the context of computing and information technology research, it refers to taking the action of introducing a computing and information technology solution then evaluating and reflecting on its value. Action research has been demonstrated in transdisciplinary research with its participatory and collaborative focus used as a driver for the interaction between many disciplines along with the broad context of taking action on the broad transdisciplinary innovation (Djanibekov et al., 2012).

This article presents a bottom-up approach that follows a structured path to transdisciplinary innovation. A method is presented that demonstrates how a set of collaborative constructive research projects progress from disciplinary innovation to multidisciplinary innovation and ultimately onto interdisciplinary innovation. Anchored in overlapping computer science concepts – and drawing on the constructive research methodology for purposeful synthesis and integration between the projects – a greater transdisciplinary goal can emerge.

This method is demonstrated through a case study involving a set of research projects focused on big data analytics involving diverse disciplines such as computer science, critical care medicine, aerospace, tactical operations, and public health. The resultant collective vision for transdisciplinary innovation is new approaches for precision public health to maintain individual wellness within communities across their entire lifespan on earth and in space.

Where the Journey Began: Big Data Analytics in Critical Care

Critical care units provide care for patients in critical condition provisioned by complex interdisciplinary teams of healthcare professionals. The medical devices within critical care generate high-speed physiological data and are seen to be a significant untapped resource in healthcare today. For big data analytics to create value in healthcare, new robust big data infrastructures to support clinical research and real-time clinical decision support are required (McGregor, 2018).

One of the most significant perinatal health problems in industrialized nations is premature or preterm birth, which is defined as birth before a gestational age of 37 weeks. Neonatal intensive care units (NICUs) are complex critical care environments requiring real-time technologies correlating medical data from multiple sources to assist with the detection of the potential onset of complications of prematurity such as infection or damage to developing brain, lungs, or eyes (McGregor, 2013a). At the turn of the millennium, the author recognized that neonatal intensive care – and critical care generally – would benefit from what would become known as a big data analytics platform to enable a systematic, reliable, and scalable approach for the analysis of the big data in the NICU (McGregor et al., 2002). Ultimately, the Artemis project (Blount, 2010), named after the Greek goddess of childbearing, was born from constructive research that leveraged high-speed physiological data together with other electronic health record data from the neonatal intensive care unit at The Hospital for Sick Children in Toronto, Canada, for earlier onset detection of the development of multiple conditions by multiple premature and ill full-term infants in multiple locations. The constructive approach divides the research process into six phases (Kasanen et al., 1993), which are listed in Table 1 along the corresponding phases of the creation of the Artemis platform.

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Table 1. Phases of constructive research undertaken in the creation of the Artemis platform

Phase	Constructive Research	Artemis Constructive Research
1	Find a practically relevant problem that also has research potential.	How can we provide healthcare professionals in critical care with new clinical insights on multiple conditions derived from the analysis of physiological data for multiple patients in multiple locations using multiple real-time streams of physiological data?
2	Obtain a general and comprehensive understanding of the topic.	Disciplinary understanding of current state of research for platforms to enable real-time analysis and synthesis of physiological data streams. Disciplinary understanding of the current state of research for physiological data behaviours prior to the clinical suspicion of late-onset neonatal sepsis (LONS) as an initial clinical test case.
3	Innovate (i.e., construct a solution idea).	Create the Artemis big data analytics platform. Create the LONS algorithm using the Artemis platform.
4	Demonstrate that the solution works.	Acquire data from neonatal infants in the NICU, The Hospital for Sick Children (Toronto) and the Women and Infants Hospital (Providence, Rhode Island, USA). Complete pilot research studies at each location for the detection of LONS in real-time as a parallel test to clinical practice to demonstrate potential (McGregor, 2011, 2013a; McGregor et al., 2013).
5	Show the theoretical connections and the research contribution of the solution concept.	Contributions to computer science in the areas of event stream processing through the deployment and commercialization of IBM's InfoSphere Streams software by IBM as a result of McGregor's First of a Kind collaboration with IBM to develop and test InfoSphere Streams within the medical context (Blount, 2010). Contributions to data warehousing through the creation of the Artemis platform (McGregor, 2013a), and temporal data mining through McGregor's patented Service-Based Temporal Data Mining framework (McGregor, 2009). Contributions to health informatics in the area of clinical decision support. Contributions to medicine in the area of pathophysiology indicators in physiological data for LONs.
6	Examine the scope of applicability of the solution.	This systemic platform is capable of performing complex analytics on physiological data within and outside the healthcare facility.

The initial practically relevant problem led to disciplinary innovation through the construction of the Artemis online software platform through a strategic partnership between researchers at the University of Ontario Institute of Technology and IBM Research. The Artemis platform is shown in Figure 1.

The development of the Artemis platform further led to disciplinary innovation in the creation of initial features within physiological data that may be predictive for the earlier onset detection of late-onset neonatal sepsis (LONS) by a neonatologist based at the Hospital for Sick Children, Toronto (McGregor et al., 2013).

Multidisciplinary research followed these two disciplinary innovation phases with the translation of the initial physiological features thought to be predictive for the earlier onset of LONS into analytics within the online analytics component of the Artemis platform. This research was considered multidisciplinary given that the researchers from computer science and medicine worked, as defined by Rosenfield (1992), in parallel with their disciplinary-specific bases to address a common problem. The real-time analytics determined whether features existed within individual physiological data and created a score based on how many features were evident (Blount et al., 2010; McGregor et al., 2013).

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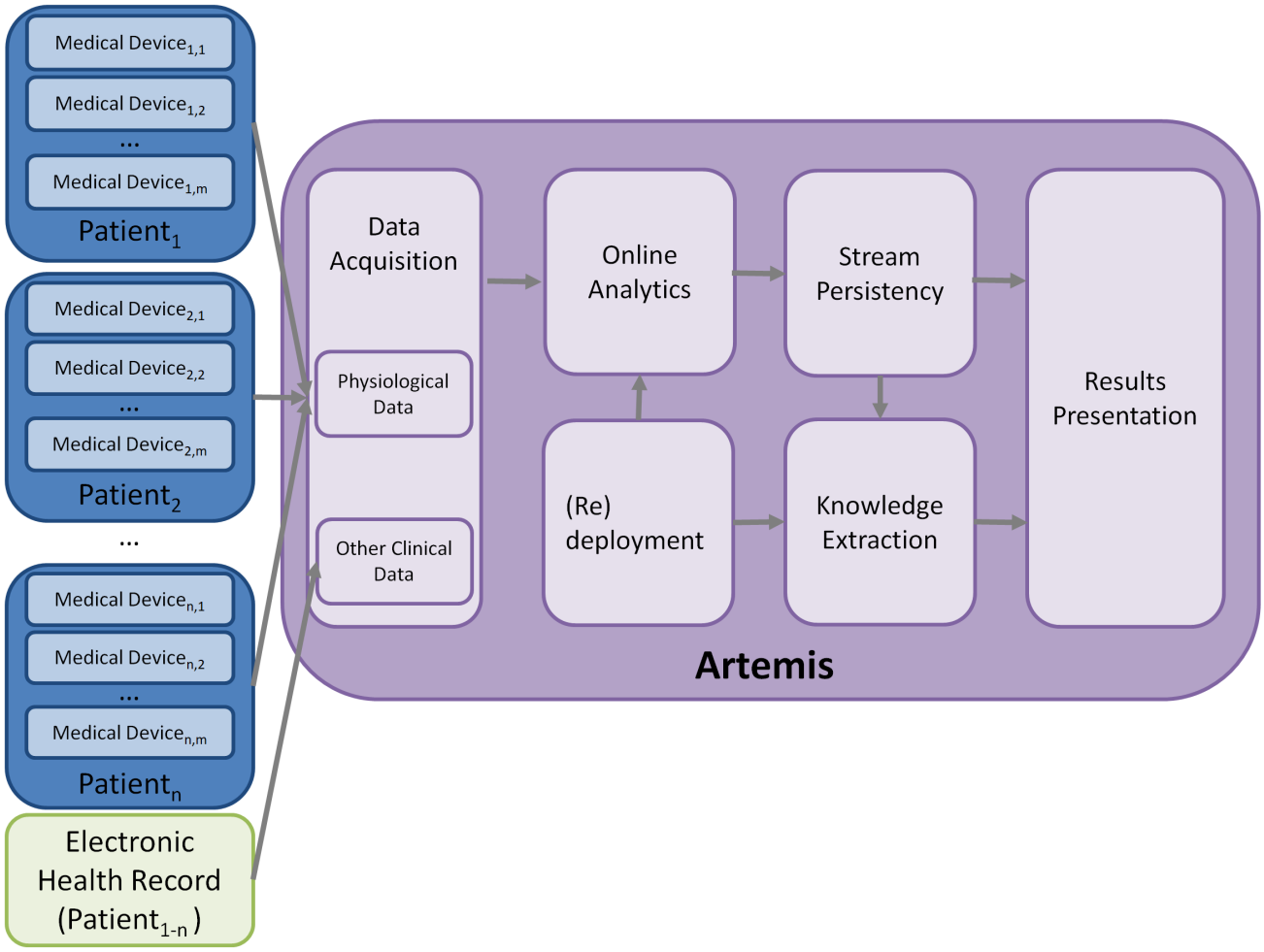

Figure 1. The Artemis platform (modified from McGregor, 2013a)

Multidisciplinary research evolved to interdisciplinary research as the technical and clinical teams learned more about the other domain. Interdisciplinarity consists of researchers working jointly but still from a disciplinary-specific basis to address a common problem (Rosenfield, 1992). This process led to an interdisciplinary research study to perform data mining and knowledge discovery for previously unknown new physiological features that were highly correlative with LONS (McGregor et al., 2012). Specifically, the discovery that the interplay between heart rate variability (HRV) and respiration variability (RRV) features as a means to remove false positives in sepsis detection that occur when HRV alone is used.

The final phase of the constructive research that created the Artemis platform led to reflection on the broader scope of applicability of the functionality of the Artemis platform for the real-time assessment of physiological data. Presentation of the Artemis platform in public and academic contexts, and interaction with professions from other domains, ultimately resulted in the application of the principles of Artemis to two distinctly different domains namely: 1) tactical operator resilience assessment and development and 2) space medicine for adaption assessment and wellness in space.

Beyond Critical Care: Big Data Analytics in Tactical Officer Resilience Assessment and Development

Tactical officers are highly trained paramilitary responders whose role is to tackle significant life-threatening situations that are outside the capabilities of front-line police officers (McGregor & Bonnis, 2017). The mental and physical stress on the body during tactical activities is intense. The rise in sympathetic nervous system

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activity leads quickly to a dramatic rise in heart rate during tactical combat activity, which is followed by further heart rate increases and respiration increases as combat continues (Grossman & Siddle, 2000). Tactical officers train regularly because skills such as precision weapon firing and tactical operations are perishable. However, frameworks to measure physiological response metrics for mental and physical reaction to tactical training as a means to assess skills competency and resilience remain a challenge (McGregor et al., 2015). Virtual-reality-driven training activities for tactical officers are increasingly being used for standardized training scenarios because they are a safe and cost-effective way to promote resilience training by allowing trainees to learn techniques for resilience from various stressors. McGregor, Bonnis, and Stanfield (2017) saw significant potential to explore new approaches for precision training of tactical operators through physiological monitoring that leveraged the advanced heart rate and breathing analytics within Artemis that was synchronized and integrated with training that is provisioned through a serious first-person shooter game that uses virtual reality.

A second constructive research project commenced within the context of tactical officer training, specifically for the assessment and development of resilience to create the Athena platform, which is named after the Greek goddess of warfare and wisdom. Table 2 presents a summary of the constructive research phases in this second project.

The initial practically relevant problem led to disciplinary innovation through the construction of the Athena platform as an extension to the Artemis platform. Athena enabled the integration of physiological data together with a real-time stream of gameplay information from the first person shooter game, the ARAIG Haptic garment, and ArmA 3. The Athena platform is shown in Figure 2.

The platform further led to disciplinary innovation in tactical training through the creation of training scenarios for clearing buildings, which included a structured approach to the inclusion of a range of stressors such as engaging with the enemy and seeing a team member injured.

Table 2. Phases of constructive research undertaken in the creation of the Athena platform

Phase	Constructive Research	Athena Constructive Research
1	Find a practically relevant problem that also has research potential.	How can we provide a new approach for the assessment of physiological data during tactical operator training to create new approaches for the assessment of resilience and the impact of stressors?
2	Obtain a general and comprehensive understanding of the topic.	Disciplinary understanding of current state of research for resilience assessment and physiological behaviours when under stress.
3	Innovate (i.e., construct a solution idea).	Create Athena big data analytics platform as an extension to the Artemis platform to enable the inclusion of additional streams of data from a virtual reality game. Create resilience assessment algorithms using the Athena platform.
4	Demonstrate that the solution works.	Perform an initial pilot study with Tactical Operators using ArmA 3, ARAIG, and Athena.
5	Show the theoretical connections and the research contribution of the solution concept.	Structured approaches for resilience assessment and development training for tactical operators. Contributions to computer science in the areas of data warehousing to create the Athena online software platform and serious games through the creation of a building-clearing serious game for use by tactical operators that enables resilience assessment and development.
6	Examine the scope of applicability of the solution.	This systemic platform is capable of performing complex analytics on physiological data within and outside the training facility.

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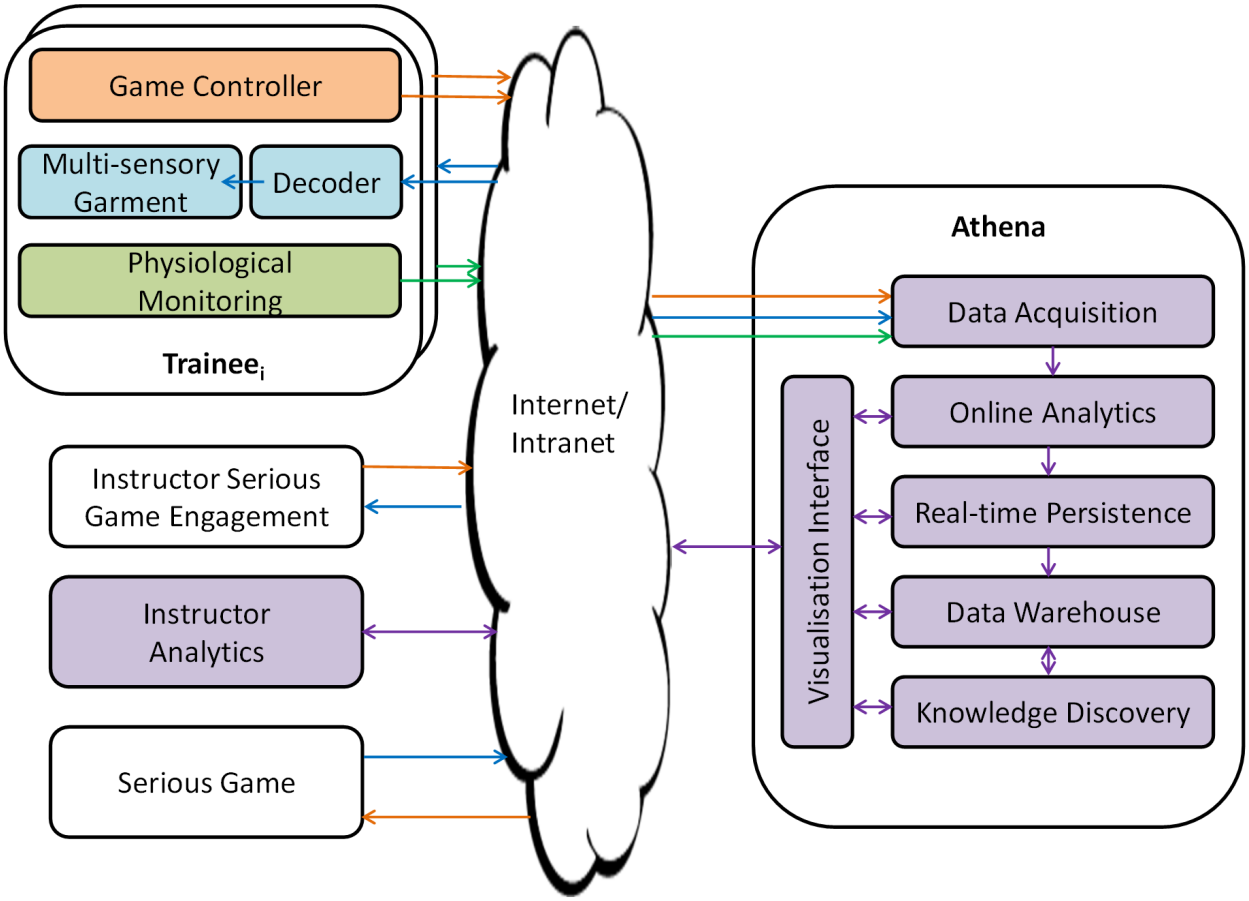

Figure 2. Integration of Athena, ArmA 3, and ARAIG (modified from McGregor et al., 2017)

Multidisciplinary research followed these two disciplinary innovation phases with the translation of the training scenario into ArmA 3. Multidisciplinary research evolved to interdisciplinary research as the technical and tactical teams learned more about the other domain. This process led to interdisciplinary research to study methods for resilience assessment and development based on structured approaches to stressor integration and new resilience analytics.

The final phase of the constructive research that created the Athena platform led to reflection on the broader scope of applicability of the functionality of the Athena platform for other first responders such as firefighters and paramedics. It also led to the realization that the resilience analytics had a broader applicability within the first responder community and those with mental health conditions such as post-traumatic stress disorder.

Beyond Earth: Big Data Analytics in Space for Adaption Assessment

A primary focus of space medicine is the estimation of risks of pathology development during long-term space flights as crew member illness or decreased performance can put the whole mission at risk (Orlov et al., 2017). Beyond the impact of weightlessness and radiation, astronauts have the potential to develop a range of medical conditions that could be developed when they are not participating in space flight. The earliest and accurate detection of the potential onset of these conditions through predictive diagnostics is of significant importance, particularly when the missions involve significant time intervals of days or weeks, where contact with mission control is not possible (McGregor, 2013b). A mathematical model of human functional states utilizing heart rate variability (HRV) analysis has been the subject of prior Russian research in space

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medicine (Baevsky et al., 2011). However, that research was limited to the determination of a 24-hourly human functional state score derived from averaging the functional states for each 5-minute window in a 24-hour period, resulting in significant data loss. In addition, data collection was a separate process from data analysis, with data collection occurring on the spacecraft, most recently the International Space Station. Using that approach, data is transported or transmitted to Earth for retrospective analysis after completion of the mission.

Therefore, a third constructive research project commenced within the context of space medicine and specifically for the assessment of adaption and response to the stress of space flight to create the Artemis in Space platform. A summary of the constructive research phases undertaken in this third project is presented in Table 3.

This research built on disciplinary innovation in functional state and wellness assessment during space flight. Multi-disciplinary research involved the translation of the function state algorithm into a stream processing algorithm to run in real-time within the Artemis in Space platform (Orlov et al., 2017).

Multi-disciplinary research evolved to interdisciplinary research as the technical and space medicine teams learned more about the other domain. This led to an interdisciplinary research study to methods for adaption assessment.

Again, the final phase of the constructive research led to reflection on the broader scope of applicability of the wellness approach and the realization that the wellness analytics had a broader applicability for providing health analytics in the broader community.

Table 3. Phases of constructive research undertaken in the creation of the Artemis in Space platform

Phase	Constructive Research	Artemis Constructive Research
1	Find a practically relevant problem that also has research potential.	How can we provide new approaches for the assessment of physiological data during space flight and analogue isolation to create new approaches for the assessment of adaption?
2	Obtain a general and comprehensive understanding of the topic.	Disciplinary understanding of current state of research for space adaption and physiology in space. Disciplinary understanding of current approaches for the analysis of space physiology
3	Innovate (i.e., construct a solution idea).	Create Artemis in Space big data analytics platform as an extension to the Artemis platform that enables analysis of adaption. Re-engineer functional state mathematical model to create adaption assessment algorithms using the Artemis in Space platform.
4	Demonstrate that the solution works.	Perform an initial pilot study with cosmonauts completing isolation experiment in Mars 500 facility.
5	Show the theoretical connections and the research contribution of the solution concept.	Medical contributions for new approaches to adaption and wellness assessment resulting in theoretical contributions to the function of health monitoring in space. Computer science contributions for real-time health monitoring in space resulting in theoretical contributions for analytics platforms that enable autonomous health monitoring.
6	Examine the scope of applicability of the solution.	This systemic platform is capable of performing complex analytics on physiological data within the spacecraft and outside it through the transmission of data to mission control.

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The Emergence of Transdisciplinary Research and Innovation for Precision Public Health with Big Data Analytics

Drawing on step 6 of the constructive research methodology to *structure a path* for the purposeful synthesis across these three separate research initiatives anchored in similar big data analytics platforms has resulted in a broader transdisciplinary research and innovation collaboration to emerge with the socially relevant issue of precision public health as the focus. Specifically, assessing the scope of applicability enabled cross-pollination between the projects for a broader health and wellness goal that draws on the knowledge gained from all projects. This partnership has been further enabled through a strategic partnership with a fourth sector: public health with the Department of Health in Western Australia. The structured path of synthesis resulted in a collaboration that transcends beyond and integrates disciplinary paradigms across computer science, critical care medicine, aerospace, tactical operations, and public health. New research and innovation projects are now emerging to link abstract and case-specific knowledge such as the concepts of health, stressors, resilience, and adaption in a broader goal of precision public health assessment of wellness to emerge. This transdisciplinary team is now proposing new action research projects to use the assessment of stressors, resilience, and adaption through big data analytics on physiological response with environmental information as an ongoing approach to proactively assess wellness within several diverse communities including, but not limited to, preterm infants, first responders, and astronauts. This work is being progressed with a new collaboration with the Western Australian Department of Health, who are international leaders in the area of precision public health for policy-driven proof-of-concept projects.

Conclusion

This research presents a method that enables research and innovation projects to progress from disciplinary innovation to multi-disciplinary innovation, which can then evolve to interdisciplinary innovation with deeper cross-domain understanding. The final stage of the constructive research process enables a structured path for a greater transdisciplinary goal to emerge.

This method was demonstrated through a set of big data analytics research projects involving diverse disciplines such as computer science, critical care medicine, aerospace, tactical operations, and public health that result in new approaches for transdisciplinary innovation in precision public health. This method enables a structured path to elevate to transdisciplinary collaboration and can then be followed by further action based transdisciplinary research projects involving this diverse team.

About the Author

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Keywords: transdisciplinary innovation, big data, critical care, resilience, adaption, precision public health

From Importing Innovations to Co-Producing Them: Transdisciplinary Approaches to the Development of Online Land Management Tools

Alex Baumber, Graciela Metternicht, Peter Ampt,
Rebecca Cross, and Emily Berry

> *"The innovator plays an important role in the diffusion process: that of launching the new idea in the system by importing the innovation from outside the system boundaries.*
>
> Everett M. Rogers (1931–2004)
> Communication theorist and sociologist
> In *Diffusion of Innovations* (2003)

While traditional approaches to innovation diffusion often assume that innovations come from outside a local system, transdisciplinary co-production offers an alternative paradigm in which local stakeholders are engaged as co-producers of innovations. The use of digital online tools for agriculture, conservation, and citizen science is an area of expanding opportunities, but landholders are often dependent on tools developed outside their local communities. This article looks at the potential for transdisciplinary co-production to be used as a framework for more participatory development of digital online land management tools, with a case study from the Central Tablelands of New South Wales, Australia. This research has implications beyond rural land management to other industries and contexts where reflexive and integrative strategies are needed to overcome barriers to stakeholder participation and engagement with new technologies.

Introduction

As demonstrated by the quotation that opens this article, innovation diffusion is often conceived of as a process of importing innovations into a system from outside, with local stakeholders then deciding whether to adopt them. However, such an approach can result in the knowledge, values, and needs of certain stakeholders being excluded from the innovation process. This can be particularly problematic for the development and application of digital technologies in rural and remote areas, where factors such as Internet access, technological proficiency, education, age, and cultural background can impact on the capacity of local community members to adopt and utilize technological innovations (Carver et al., 2009; Cinnamon & Schuurman, 2013; Haklay, 2013; Radil & Anderson, 2018). Transdisciplinary approaches offer an alternative to the notion of "importing" innovations by engaging multiple stakeholders and knowledge types in the innovation process, including diverse types of disciplinary and expert knowledge as well as practical and local knowledge (Lang et al., 2012). Transdisciplinary approaches are relevant not only to rural land management but also to a diverse range of contexts including urban planning (Polk, 2015), waste management (Smith, 2017), health (Darrell, 2016), and higher education (Petra & Christian, 2017).

Digital online tools for rural land management are a growing area of interest for academic research and industry development. This trend encompasses both agricultural production and conservation-based management and may be framed as digital agriculture (Trindall et al., 2018), spatial decision support systems (Ramsey, 2009), participatory geographic information systems (Radil & Anderson, 2018), or citizen science (Newman et al., 2017). Advances in geospatial data and

tools can facilitate greater collaboration by enabling groups to communicate better, divide up tasks, share data, and integrate different functions such as mapping and communication (Palomino et al., 2017). Such tools also have the potential to bridge the gap between the property scale at which landholders commonly make decisions and the broader scales at which cross-property challenges need to be managed, including total grazing management, weeds, and fire (Wyborn & Bixler, 2013).

To understand the innovation process around digital online land management tools, a rich history of rural landholder research can be drawn upon. Everett M. Rogers, whose quotation opens this article, developed his innovation diffusion model after observing the adoption of agricultural innovations among Iowa corn farmers and was influenced by other researchers at Iowa State University (e.g., Ryan & Gross, 1943). His seminal 1962 book *Diffusion of Innovations* has been influential on the development of broader innovation theory, including his generalized diffusion model, which classifies adopters along a spectrum from innovators to laggards (Figure 1).

Rogers ' central argument is that innovation diffusion is a general process that follows similar patterns across diverse contexts ranging from agriculture to medicine to information technology (Rogers, 2003). However, this model has also been subject to criticism, particularly in relation to rural landholders. Pannell and co-authors (2011) argue that it implies "innovativeness" is a characteristic people apply equally to all innovations, while Vanclay (2004) argues that "agriculture has too long been thought of as a technical issue involving the application of science, and the transference of the outputs of that science via a top-down process of technology transfer" (Vanclay, 2004).

In this article, we consider transdisciplinary innovation strategies that are participatory and collaborative rather than "top-down" and apply these to an Australian case study involving the development of a digital online land management tool. Specifically, we apply the framework for "transdisciplinary co-production" developed at Mistra Urban Futures in Sweden (Polk, 2015). In doing so, we seek to demonstrate the versatility of this framework by applying it outside of the urban context in which it was originally developed and on the other side of the world.

Transdisciplinary Co-Production

Transdisciplinarity has been defined in different ways over time (Scholz & Steiner, 2015a), but a central feature of many definitions is the need for participatory engagement with a range of stakeholders. Smith (2017) highlights the influence of participation and deliberative democracy on the development of transdisciplinarity from the 1970s onwards. Similarly, Polk, and Knutsson (2008) emphasize the importance of participatory approaches to transdisciplinary knowledge production in order to incorporate contextualized knowledge, transgress disciplinary boundaries, and subsume "a variety of different non-academic stakeholders, organizations and sites". Scholz and Steiner (2015b) present a vision of transdisciplinarity that cuts across disciplinary boundaries, involves multi-stakeholder discourse, includes a process of mutual learning, and focuses on practical real-world challenges.

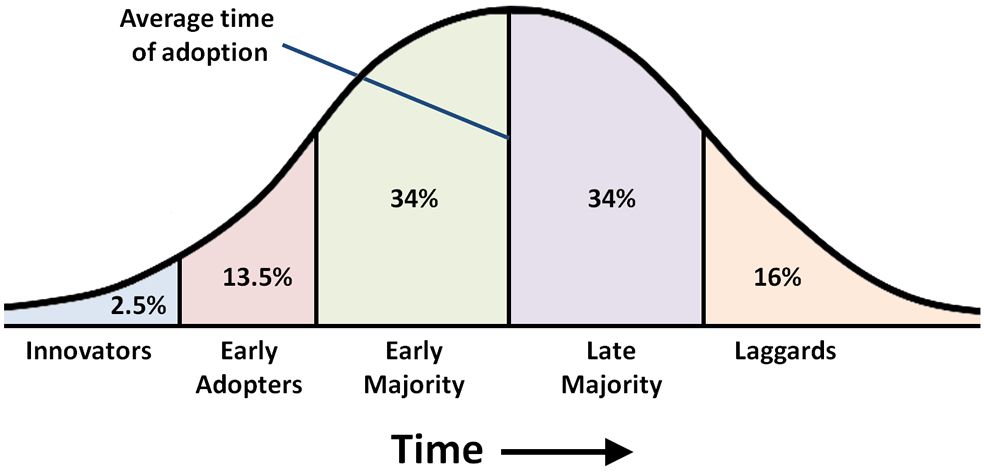

Figure 1. Generalized model of adoption over time divided into Rogers' five adopter categories (redrawn from Rogers, 2003)

The framework for "transdisciplinary co-production" evaluated in this article was developed at Mistra Urban Futures in Sweden and described by Polk (2015). The framework includes five focal areas: inclusion, collaboration, integration, usability, and reflexivity (Table 1).

While Polk (2015) considers transdisciplinary co-production in relation to urban planning, a precedent has previously been set for the application of the term "transdisciplinary co-production" to rural settings, with Aeberhard and Rist (2009) applying it to the co-production of knowledge on organic farming in Switzerland. The co-production concept also has some overlaps with the concept of "co-management" in natural resource management, which also involves bringing together multiple knowledge types in a process of social learning and adaptation (Berkes, 2009). Unlike Polk (2015), Aeberhard and Rist (2009) did not apply a specific framework for transdisciplinary co-production in their study, but their use of the term demonstrates its versatility in terms of both context and product. In the case of Aeberhard and Rist (2009), the product was knowledge about organic agriculture. For Polk (2015), the products were visions of urban planning. For our case study, the product is a digital online tool that can be used to collaborate on managing land and natural resources.

Our case study project in the Central Tablelands of New South Wales (NSW), Australia, was not initially designed using Polk's framework and the research team initially chose to frame it as an "interdisciplinary" rather than transdisciplinary project. Scholz and Steiner (2015b) define interdisciplinarity as "the merging of concepts and knowledge from different disciplines", which does not necessarily incorporate the focus on multi-stakeholder discourse and real-world practice that they view as integral to transdisciplinarity. Our case study clearly meets Scholz and Steiner's definition of interdisciplinarity, with our research team having expertise in agriculture, geospatial science, environmental management, policy studies and human geography. However, a key question considered in this article is whether the case study also qualifies as transdisciplinary. This question has relevance not only for rural land use projects but for any project that aims to develop digital technology in a manner that is collaborative, participatory and does not easily fit within disciplinary boundaries.

The Central Tablelands Case Study

The two case study areas (labelled as NE and SW in Figure 2) are located in the NSW Central Tablelands region, which lies between the Sydney metropolitan area and the NSW western slopes and plains. The dominant land use is sheep and cattle grazing (NSW Government, 2007), but there has also been an influx of so-called "rural lifestylers" who are not dependent on the land for their income (Central West Independent Review Panel, 2007). The Landcare movement, which brings together conservation and production objectives (Curtis et al., 2014) is represented in the region by many small local groups and some larger umbrella groups such as Watershed Landcare (covering 9000 km^2 around Mudgee).

Table 1. The five focal areas of Polk's Transdisciplinary Co-Production Framework (Adapted from Polk, 2015)

Focal Area	Definition from Polk (2015)
1. Inclusion	Different groups of stakeholders from both practice and research are entitled to the entire knowledge production process.
2. Collaboration	The processes and methods for participating as well as the quality and degree of the participation result in in-depth contributions from both practice and research.
3. Integration	The assimilation, combination and/or synthesis of both practice-based and scientific perspectives, values, knowledge and expertise adequately capture the problem complexity and issues being addressed.
4. Usability	Assessment and reflection upon the social robustness and transformative capacity of outputs and outcomes occur throughout the research process.
5. Reflexivity	The project approach includes on-going scrutiny of the choices that are made when identifying and integrating diverse values, priorities, worldviews, expertise and knowledge from both practice and science in the research process.

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Figure 2. Location of the North-East (NE) and South-West (SW) case study areas in the NSW Central Tablelands (Map data: Google)

The project, undertaken between January 2016 and January 2018, aimed to assess landholder interest in using online tools to collaborate on land and natural resource management. It was funded by the NSW Environmental Trust and involved three universities (The University of Sydney, The University of New South Wales, and The University of Technology Sydney), as well as Landcare NSW Inc. (the peak body for Landcare groups in NSW) and the Central Tablelands Local Land Services (a NSW Government agency). The research team brought together a range of disciplinary expertise, as well as practical experience in commercial agriculture, conservation, and community engagement.

Prior to the start of the project, a range of existing online collaboration tools were accessible in the case study areas, including global platforms for spatial analysis (e.g., Google Earth, ArcGIS Online, QGIS Cloud) and social media (e.g., Facebook, Twitter, Instagram). In addition to these global tools, a range of national or regional-scale tools are also applicable to the Central Tablelands region, including a directory of active environmental groups on the NSW Landcare Gateway (landcare.nsw.gov.au), spatial data via the NSW Spatial Information Exchange (maps.six.nsw.gov.au) and Atlas of Living Australia (ala.org.au), and citizen science platforms such as FeralScan for reporting feral animal sightings (feralscan.org.au).

The diversity of available tools in the case study area reflects a global trend towards tools that are free, open source, inter-operable, and able to be adapted by user communities (Palomino et al., 2017). However, none of the available collaboration tools were co-produced by or with local stakeholders and the extent to which they may be able to adapt such tools to meet their local needs depends on factors such as Internet access, technological proficiency, education, and institutional support, which can pose particular challenges in rural and remote areas (Cinnamon & Schuurman, 2013; Haklay, 2013).

The case study research followed a participatory approach, with focus groups used to scope key issues and stakeholders, a participatory rural appraisal (PRA) exercise undertaken in each case study area, a questionnaire used to inform the design of an online tool, a series of adaptations made to the NSW Landcare Gateway, and follow-up workshops held to evaluate the new features. Participatory rural appraisal is an approach that treats rural people as co-producers of knowledge (Chambers, 1994). The case study methodology, following Campbell (2001) and Narayanasamy (2009), involved interview teams made up of researchers and local stakeholders spreading out across each case study area to interview and survey landholders over a period of 2–3 days, followed by a concluding workshop to synthesize key findings.

The semi-structured interviews covered land management practices, history of collaboration, interest in further collaboration, and use of online collaboration tools. At the end of each interview, interviewees were asked to complete a written survey covering their level of Internet access and usage, the functions they would most value in a new collaboration tool, requirements of a "user-friendly" tool, the types of data they would be willing to share, and their willingness to pay a fee to access an online tool. For full details of the survey methodology and results, see Baumber and co-authors (2018).

In total, 26 landholders were interviewed in the NE case study area and 29 in the SW area. The NE area had a higher proportion of small-to-medium landholders (n=17/26 interviewees), with more than half identifying as rural lifestylers with an urban background. In contrast, participants in the SW study area were predominantly medium-to-large commercial landholders (n=19/29 interviewees), with most interviewees coming from inter-generational farming families producing sheep (for meat and wool) and beef. The NE area had a more diverse mix of land use activities, including sheep for wool or meat, beef, wine, alpacas, pigs, and land managed for conservation. Interviewees were not asked their age and there was no obvious difference between the two areas in this regard.

The issues for which collaboration was practiced or desired were similar in each area, including weeds and pest animals, ecological restoration, production practices, and tourism. Key results emerging from the survey and interviews included the poor quality of Internet access experienced by many landholders (especially in the SW area), a desire to selectively share some data among a local group rather than with the general public, and an interest in sharing data in a variety of formats such as map-based data, photos, news, events, and monitoring results. Data security was a key concern, and there was a strong interest in mobile device compatibility and simple menu options to make any tool user-friendly. The interest in sharing a wide variety of data formats highlighted the importance of not defining any new tool in narrow terms such as a "mapping" or "citizen science" tool, as well as ensuring that it could be adapted in future to meet diverse and emerging landholder objectives.

The survey results were used to design a series of modifications for the NSW Landcare Gateway. This was selected as the most appropriate platform to trial new features based on the case study results for the following reasons:

- It was operated by a key project partner (Landcare NSW) who was seeking to add new functions.
- It was free for local landholder groups to use.
- Landcare NSW had the resources to keep it operating after the end of the project when funding had ceased.
- It already had much of the critical functionality identified from the social research, including dedicated spaces for local groups and the ability to handle a variety of data sources (map-based data, photos, news/events, and monitoring results).

A series of modifications were made to the NSW Landcare Gateway between March and August 2017, when trials were launched in each of the two case study regions. Figure 3 shows some of these new features, including social media feeds (left-hand side), links (top right), mapping features (sample point features and polygons displayed), and the ability to export data from the maps ("Download group KML" link at bottom right). Additional mapping functionality was added to allow users to add detailed information to each point or polygon, including text descriptions, photos, and data files for download. New sharing permissions were added so that users could choose whether data was visible to themselves only, to other group members, or to the general public. Figure 3 shows the public view for the Glideways Group page; signed-in group members would see additional features on the map. A number of back-end changes were required to make this possible, including streamlined sign-up and login processes and new editing permissions, as only group administrators previously had access rights to upload data and change display settings.

In order to trial the changes, one collaborative activity was identified for each case study area based on consultation with participants in the rural appraisal and other local stakeholders. The monitoring of spiders as an indicator of ecosystem health was selected for the NE trial, whereas in the SW area, marsupial gliders were selected as the focus of the trial (e.g., recording observations and nest box sites). Local workshops were held in August 2018 to enable landholders to learn about the new Gateway features and sign up to the trials, with 12 landholders signing up to the NE trial and 11 to the SW trial.

Further workshops were held in December 2018 to evaluate the trials' progress in each area, and feedback was also sought from individual users of the tool. Trial results to date indicate that some participants value having a space to store data and to share it with neighbours or other stakeholders such as funding bodies. However, a range of challenges has also been identified. Some issues have since been resolved, such as an inability to differentiate between different data types on maps (resolved through additional icons) and an inability to export mapping data for use in other platforms (resolved through added KML and CSV export functions). Other issues remain unresolved, such as a desire for even simpler menus with fewer clicks needed to reach each page, issues around loading speeds in areas with poor Internet access, and difficulties importing data layers of certain formats.

The current status of the project is that the project team continues to work with participating landholders to customize and evaluate the Gateway modifications. Further funding has been sought to implement additional modifications and to extend trials to additional collaborative practices, including revegetation and collaborative management of total grazing pressure.

Evaluation of Project Against the Transdisciplinary Co-Production Framework

The project is evaluated below against each of the five focal areas described by Polk (2015): inclusion, collaboration, integration, usability and reflexivity.

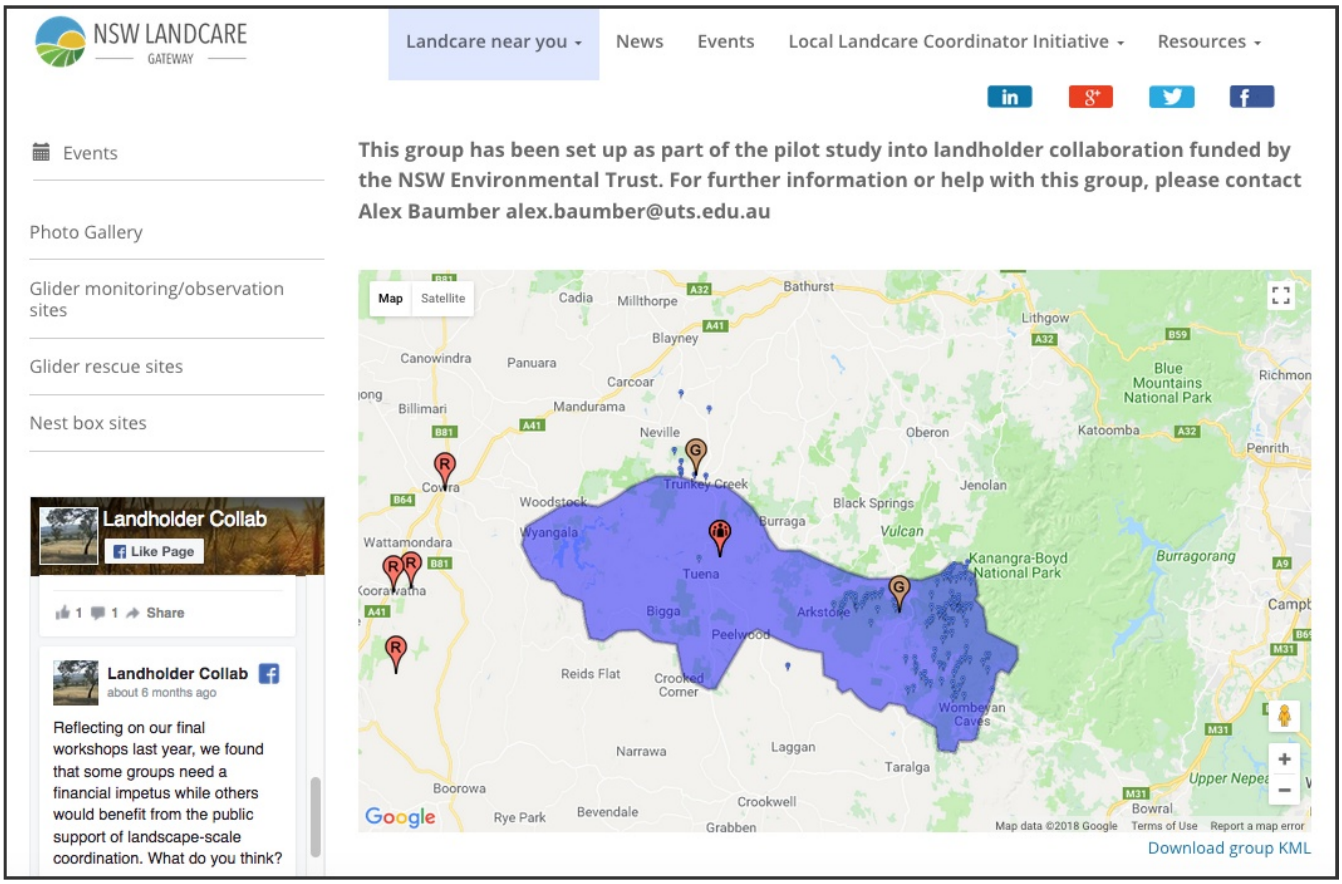

Figure 3. Screenshot showing the incorporation of text, mapping, and social media on the revised NSW Landcare Gateway

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1. Inclusion
The framework requires that "different groups of stakeholders from both practice and research are entitled to the entire knowledge production process" (Polk, 2015).

The project included several different groups of stakeholders involved in land management, including commercial farmers, non-commercial "lifestylers", government agencies, and local conservation groups. In addition, Central Tablelands Local Land Services, Landcare NSW, and key local groups were also involved in the design of the research alongside the university-based researchers.

Inclusion could be further enhanced through greater consideration of other stakeholder types. Absentee landholders (e.g., those living in cities and visiting properties on weekends) emerged as a group that was difficult to reach via the initial social research design. Agribusinesses and producer groups could also have been included to a greater degree. Other groups that were included, but only to a limited extent, were protected area managers and indigenous groups. Expertise in biology, law, and information technology was brought in at various stages to complement the disciplinary strengths of the project team, but other disciplines could have also been included, such as health, economics, and design. A greater effort could also have been made at the start of the project to map out the "entire knowledge production process", which may have identified a need to support on-ground data collection as well as developing a tool that could be used to share it.

Despite our attempts to include a diverse range of affected stakeholders, it is also possible we may have inadvertently excluded some stakeholders through the format or timing of participatory practices. For the case study, care was taken to locate workshops in appropriate locations and to time them for when most landholders would be able to attend (including some evening workshops). However, some stakeholders may have been excluded due to distance or commercial farming priorities or their inability to participate in the Landcare Gateway trial due to a lack of technological literacy or Internet access.

2. Collaboration
The framework requires that "the processes and methods for participating as well as the quality and degree of the participation result in in-depth contributions from both practice and research" (Polk, 2015).

The project was explicitly aimed at enhancing collaboration, not only in terms of the methods used to co-produce the online tool but also through the tool itself. The participatory rural appraisal methodology facilitates collaboration and the integration of different knowledge types by partnering outside researchers with local stakeholders to undertake interviews. A mixed-method approach was used that incorporated surveys to obtain short answers quickly and systematically, semi-structured interviews to obtain in-depth personal contributions, and workshops and focus groups that allowed participants to engage in conversation with one another.

3. Integration
The framework requires that "the assimilation, combination and/or synthesis of both practice-based and scientific perspectives, values, knowledge and expertise adequately capture the problem complexity and issues being addressed" (Polk, 2015).

The participatory rural appraisal interviews, workshops, and focus groups were the key project activities for assimilating, combining, and synthesizing knowledge. Experts on spiders, gliders, and legal models for collaboration were invited to the local area workshops that launched the online tool trials, allowing scientific and practice-based knowledge to be integrated. Further integration could have occurred at other project stages, such as the production of the final project report, conference presentations, and journal articles, which were influenced by landholder values and knowledge but did not involve direct landholder involvement.

4. Usability
The framework requires that "assessment and reflection upon the social robustness and transformative capacity of outputs and outcomes occur throughout the research process" (Polk, 2015).

Usability of outputs was a key consideration throughout the project. This included the initial social research to identify user needs and constraints, as well as the design phase of the tool and the subsequent user trials. The survey asked respondents which features they considered most critical for a "user-friendly" tool, with simple menu options emerging as the most highly rated feature. However, as the survey was based on a hypothetical tool, the user trials for the modified Gateway tool proved critical in identifying real-world usability issues around importing and exporting spatial data,

differentiating between different data types on maps, and further refinement of menu options to reduce the number of "clicks" required to navigate within the tool.

5. Reflexivity
The framework requires that "the project approach includes on-going scrutiny of the choices that are made when identifying and integrating diverse values, priorities, worldviews, expertise and knowledge from both practice and science in the research process" (Polk, 2015).

The project scrutinized decision making, assumptions, and value-judgments at multiple stages, including consultation on the project design, initial focus groups, key informant interviews, participatory rural appraisals, and surveys in each sub-region and follow-up workshops to evaluate the modifications to the NSW Landcare Gateway. The analysis undertaken for this article also represents part of the reflexivity dimension of the project.

The workshops and survey were especially useful at challenging assumptions and value judgements of the project team. For example, at one participatory rural appraisal workshop, researchers initially classified weed management as a conservation practice, but the consensus among landholders and agency staff was that it was more appropriately considered a production activity, due to weeds reducing the productive potential of the land. The landholder survey results also challenged our assumptions about the nature of the online tool, which was initially framed as a participatory geographic information system (PGIS) based on the prominence of PGIS approaches in the academic literature (e.g., Karimi & Brown, 2017; Meyer et al., 2016; Ramsey, 2009). However, survey respondents ranked mapping functionality below other features relating to data security, sharing settings, and the ability to search using key terms. As such, it was concluded that the tool should not be classified as PGIS but rather as an adaptive collaboration tool capable of incorporating multiple data types, including text, photos, news/events, and maps.

A final consideration relating to reflexivity is the extent to which the product of a co-production process should be adaptable to changing values and knowledge after the end of the project. Once the diversity of potential uses of the tool were identified through the survey, the tool was explicitly designed to be adaptive in the sense that new user types could be added, future users could choose how they used different functions and the types of data included could be altered to reflect changing needs and values. The adaptive capacity of the tool is limited by technical and design constraints, but an explicit aim in its design was to leave space for self-organization among users and reflexive processes that re-evaluate assumptions and value judgements about how it should be used in an ongoing fashion.

Discussion and Implications

The application of Polk's (2015) transdisciplinary co-production framework to this case study has implications beyond the NSW Central Tablelands for the development of digital online tools more broadly and for the application of transdisciplinary innovation strategies to other contexts. Overall, we argue that our case study qualifies as an example of transdisciplinary co-production, as it addresses all five of Polk's focal areas and landholders in the project were viewed as co-producers of an innovative digital tool rather than potential adopters of an innovation brought in from outside the system. However, while collaboration, usability and reflexivity were addressed strongly, the other two focal areas of inclusion and integration could have been addressed to a greater extent.

With regards to inclusion, certain stakeholder groups may have been disadvantaged by distance or Internet access and others could have been engaged more fully, such as agribusinesses, producer groups, protected area managers, and indigenous land managers. Challenges around Internet access, technological literacy, and the incorporation of indigenous knowledge are common to other studies in rural or remote areas (Carver et al., 2009; Wang et al., 2008) and are important factors to take into account when applying Polk's transdisciplinary co-production framework outside the urban context in which it was first developed. However, it is also important to remember that the exclusion of marginalized groups is an issue across the diverse contexts in which digital online tools are applied, with participation influenced by factors such as gender, education, and affluence (Haklay, 2013).

As with inclusion, the integration of different knowledge types can be a challenge for digital collaboration tools more broadly (Palomino et al., 2017). For the case study, integration could have been enhanced by including a greater diversity of stakeholders in the project reporting stages. However, other stages of the project highlighted effective ways to integrate expert disciplinary knowledge alongside local and practical knowledge. The participatory rural appraisal practice of partnering outside researchers with local stakeholders when undertaking interviews purposely encourages

the integration of different knowledge types and has relevance beyond rural contexts and online tools. The case study also highlights the important role that reflexivity plays in the integration of knowledge by challenging underlying assumptions (e.g., about weeds being a conservation issue or tools being framed primarily as mapping tools) and thus opening participants' minds to new perspectives.

One potential refinement to Polk's 2015 framework that emerges from the case study is the need to consider the five focal factors not only in relation to how the "products" of transdisciplinary co-production are initially developed but also in how they are managed and refined into the future. In the Central Tablelands case study, an explicit aim of the project was to develop a tool that was adaptive to changing stakeholder values and knowledge over time. As such, the transdisciplinary co-production process necessarily involves a degree of "co-management" after a product is launched. In considering what form this ongoing co-management should take across diverse contexts, natural resource management may offer potential insights through the tradition of "co-management" around land and natural resources (Berkes, 2009). "Adaptive co-management" takes this further, with landholders, governments, and other stakeholders working together to manage natural resources through deliberate experiments and a process of mutual learning (Armitage et al., 2008).

Conclusion

In contrast to the view expressed by Everett M. Rogers in his seminal work *Diffusion of Innovations,* transdisciplinary approaches recognize that innovations need not be imported from outside but can arise from the integration of diverse knowledge types within a local system through a reflexive and collaborative process of mutual learning. Our application of Polk's (2015) framework for transdisciplinary co-production to the development of an online collaboration tool in the NSW Central Tablelands has revealed a range of insights that are relevant to the local context. These include the need to consider Internet access, technological proficiency, and indigenous knowledge when developing online collaboration tools. However, it has also provided insights relevant to a diverse range of contexts, including strategies for integrating expert and practice-based knowledge, the value of reflexive approaches that challenge underlying assumptions, and the need for ongoing co-management to be considered as part of the transdisciplinary co-production process.

Just as Rogers' innovation diffusion model grew from research with Iowa corn farmers to encompass a wide range of contexts, the insights gained from the application of transdisciplinary co-production to rural land management has implications for many different industries and geographic settings. By encouraging collaboration, the integration of knowledge, and the evaluation of underlying assumptions about the innovation process, transdisciplinary approaches can provide strategies for enhancing stakeholder inclusion and the usability of new technological innovations.

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Transdisciplinary Research in the Built Environment: A Question of Time

Paula Femenías and Liane Thuvander

> *"We had the technical part ready but realized that this was the simple part of the challenge."*
>
> Industry partner in project ReBo,
> a transdisciplinary research project described in this study

In this article, we reflect on 14 years of experience with transdisciplinary research in the built environment. We critically consider challenges and pitfalls in relation to normative definitions of transdisciplinary research derived from the literature. Our experiences from five transdisciplinary research projects are presented with a focus on each project's aim, size, organization of work, and funding. Results show that different kinds of transdisciplinary research approaches co-exist and that these can serve different purposes and situations. In most cases, transdisciplinary projects lead to raised levels of awareness of the complexity of real-world problems among participating partners. In some cases, the outcome is a useful innovation, in order to support such innovation, a focus on real cases is encouraged. However, there might be a trade-off between the focused attention on a real case and the maintained interest among diverse participants in a larger project. An important insight is that innovation and knowledge development through transdisciplinary settings take time. It is favourable for the development of networks, common visions, trust, and innovation if consecutive transdisciplinary projects can be arranged with the same partners. We conclude the article by providing practical guidelines to support the management of transdisciplinary projects.

Introduction

Transdisciplinary research approaches have been brought forward as a means to solve and mitigate real-world problems where disciplinary and interdisciplinary research approaches fall short. Transdisciplinary research or "Mode 2" knowledge production, in contrast to traditional disciplinary "Mode 1" research, brings together researchers from different disciplines with non-academic stakeholders from industry, the public sector, and civil society in order to address and develop applicable solutions to societal problems (Brandt et al., 2013; Gibbons et al., 1994; Lang et al., 2012; Spangenberg, 2011). Key benefits of this new paradigm are that it transcends disciplinary boundaries and brings in knowledge from various communities of knowledge –including from outside academia. Transdisciplinary research also goes beyond problem analysis in search for efficient guidance, strategies, and innovation. Through collaboration with stakeholders, legitimacy and ownership are created, which in turn build potential for the up-take of innovation.

Transdisciplinary approaches have been found especially relevant in the field of sustainability science as it is normative and problem-solving oriented (Lang et al., 2012). With its lack of innovative power, transdisciplinary approaches also have particular relevance for the built environment (Sexton & Lu, 2009). The complex nature of the building industry makes it essential for the research community to engage with stakeholders as a means to reach higher degrees of applicability, for example in relation to innovation for energy efficient technologies (Berker & Bharathi, 2012; Oreszczyn & Lowe, 2009). In addition, in Sweden, research funding agencies increasingly emphasize academia–industry collaboration by requiring participation and co-funding from non-academic stakeholders on topics related to sustainable development of the built environment. This co-funding can reach up to 50 % of the project budget in order to be legitimate and can be in-kind or ready assets.

In this article, we reflect on our practical experiences when engaging in transdisciplinary research in the

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built environment with the aim to contribute to the development of practical guidance for the management of this kind of knowledge development and innovation.

Our approach is qualitative and the method is identified as reflexive retrospective (Mitev & Venters, 2009). A reflexive approach deviates from traditional post-hoc accounts in which the success of pre-defined objectives and deliverables are assessed by attempting to capture the experiences of the researchers and the non-academic partners. We broadly follow Alvesson and Sköldberg's (2009) four levels of reflective interpretation, as further developed by Mitev and Venters (2009). The four levels include reflective interpretation of:

1. The empirical material.

2. The project partners' perspectives in relation to the empirical material.

3. The empirical material in relation to the earlier accounts of transdisciplinary research.

4. Our own personal relationship to the studied object.

Although we have experiences from about 15 transdisciplinary research projects spanning a period of 14 years, here we focus on five projects – Demo04/06, 3iii, ReBo, SIRen, and STED – that are summarized in Table 1. The projects vary in size, in terms of participants and budget, and in organization of work, but they also represent a continuous line of investigation through consecutive projects.

The reflexive retrospective approach draws on the analysis of empirical material from the projects (e.g., observations, presentations, meeting notes, reports, publications, and other project documentation), which have been interpreted along with memories of the authors. In addition, in the projects Demo04/06 and 3iii, interviews were made with all participants during the course of projects to capture expectations and experiences, and in the case of ReBo and SIRen (Table 1), post-project surveys among all participants. The reflection itself was made through discussions between the authors, by writing this article, by responding to the editors' and a reviewer's suggestions, and by interpreting the experiences and visualizing them in figures.

The article is structured as follows. The first two sections briefly summarize definitions and challenges for transdisciplinary research found in the literature. After that, results as well as our reflections from five transdisciplinary projects are presented. The presentation follows the same structure for each project describing their aim and approach, innovation and learnings produced, and outcomes. Next, we discuss our reflections in relation to earlier experiences of transdisciplinary research. Finally, we conclude by presenting a number of guidelines for the management of transdisciplinary research projects.

What is Transdisciplinary Research?

Lang and co-authors (2012) argue that it is not possible to give a recipe or general definition of transdisciplinary research as it is in the nature of these projects to be embedded in specific contexts. Indeed, the case-specificity makes it difficult to generalize practical experiences (Bresnen & Burrell, 2013; Lang et al., 2012). Nevertheless, the literature in the field does identify some commonalities.

Gibbons and colleagues (1994) formulated the original and well-cited thesis for what they called "Mode 2" as a complementary and new way for knowledge production to deal with problems that could not be circumscribed by a single existing disciplinary field. According to them, Mode 2 knowledge production is characterized by five attributes:

1. Producing knowledge in a context of application. The context-specific and problem-solving nature of Mode 2 is organized to meet needs of a particular social setting as opposed to norms and rules of a particular discipline. The project should be responsive to the emergent situation.

2. Transdisciplinary, demanding real-world problem settings and integration of different disciplines and skills.

3. Heterogeneous and organizationally diverse. The real-world problem requires transient teams whose membership changes to respond appropriately to the emergent situation.

4. Socially accountable and reflexive. The participants need to be sensitive to the actual and perceived impacts of their activity by interests outside the action group necessitating a deeper appreciation of the research process itself on the part of the participants.

5. Diverse quality controls that reflect the concerns of a broader community of interest.

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Based on a review of a larger number of transdisciplinary research projects, Lang and co-authors (2012) describe three phases that such projects follow. In the first phase, the collaborative team is set up and together they develop an understanding of the problem and decide upon models for working. It is essential in this phase that the real-world problem is translated into a boundary object, meaning an object or a concept that serves as an interface between the boundaries of different disciplines, organizations, and cultural communities. A boundary object has been described as socially enacted and open for interpretation and negotiation (Styhre & Gluch, 2010). It should be fluid enough to bridge various communities while at the same time robust enough to maintain a common identity across sites (McGreavy et al., 2013). Another key aspect in the first phase is to develop a "common language" among participants. In the second phase, the research is coproduced. Finally, in the third stage, knowledge should be re-integrated and applied both in scientific and societal practice. Lang and co-authors (2012) emphasize that the produced knowledge can be tools or enhanced processes but can also be more indirect results such as learnings and new perspectives.

Even if there are many commonalities and a consensus about the main features of transdisciplinary research, there is still a disagreement about their reciprocal importance. Transdisciplinary research has been criticized for reinforcing the loss of academic autonomy and adding to the subordination of academic science to market forces (Grey, 2001). Balsiger (2004) questions the real scientific need for transdisciplinary research and argues that it is more a principle than a scientific approach. Shinn (2002) describes transdisciplinary research to be more of a social platform than a scientific methodology. Leydesdorff and Etzkowitz (1998) argue that the increasing academy–practice collaboration is not so much a result of a transition towards Mode 2 research but a cause for this development, as society is characterized by a "disorganization" of institutional barriers.

Several authors argue that there is no clear distinction between Mode 1 and Mode 2 research and they instead mostly overlap (Bresnen & Burrell, 2013; Ziman, 1996). Pohl and colleagues (2010) state that transdisciplinary research does not have to be participatory (Pohl, 2011). Elzinga (2008) says that the degree of participation depends on the goal of the project. What is important is to reach valuable knowledge that grasps the complexity, takes into account diverse perspectives, links the abstract and the case specific, and develops both descriptive and practical knowledge for the "common good" (Pohl, 2011). Spangenberg (2011) suggests a distinction between science *for* sustainability (rather monodisciplinary) and science *of* sustainability (interdisciplinary and transdisciplinary).

A controversy is apparent with respect to descriptive and practical knowledge in transdisciplinary research, also called "knowledge first" or "process-orientation" (Miller, 2013; Wittmayer & Schäpke, 2014), and whether the scientist should take a role as "descriptive analyst" or "transformational activist" (Wiek et al., 2012). The process-orientation approach emphasizes relevance and actionable knowledge, defined as knowledge that can "change professional practice or social institutions through active and transformative participation of those working within a particular setting" (Crawford, 1995). The creation of an arena (Eden et al., 2005; Falkheden & Malbert, 2004; Loorbach, 2007; (Pohl et al., 2010) is a core activity in process-oriented projects, to host meetings, discussions, and reflections to support social learning. Such arenas have been described as a protected space (Loorbach, 2007) or a neutral space where participants can meet on an equal footing, beyond the constraints of roles, power dynamics, and limitations of specific projects (Falkheden & Malbert, 2004). Transdisciplinary projects should benefit from a non-hierarchical approach to knowledge production (Balsiger, 2004). These social platforms and protected spaces need to be maintained during the course of the projects (Wittmayer & Schäpke, 2014), and regular meetings should be held on an ongoing basis to support the interest in the group (Deprés et al., 2004).

Challenges of Transdisciplinary Research

Reported practical insights from working with transdisciplinary projects show that the transition from Mode 1 to Mode 2, and on to more collaborative science, is not effortless. Conflicts have been observed in projects where the expertise of institutions has been devalued and where existing hierarchies have been challenged (Berker & Bharathi, 2012). Interdisciplinary meetings can lead to conflicts about ontologies and methodologies, while the transdisciplinary approach in itself can be problematic in terms of producing legitimate results that are acknowledged as reliable and valid (Lang et al., 2012; Wiek et al., 2012). Suspicion that academic knowledge is inadequate for use in practice might also be prevailing (Argument et al., 1998). Furthermore, joint knowledge production can suffer from confounded

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agendas, reluctance to face exposure, and varying value preferences (Wiek et al., 2012). Lang and co-authors (2012) and Wittmayer and Schäpke (2014) describe challenges with unbalanced ownership of problems, insufficient legitimacy of the team or the actors involved, and the fear of failure. There can also be a mismatch between academics wishing to offer solutions that will be implemented in the long term and companies seeking to implement short-term solutions to the problems they are experiencing today (Argument et al., 1998; Falkheden & Malbert, 2004). Also, some academics have experienced proprietary control of results on the behalf of participating companies, something that will inhibit open knowledge development and diffusion (Lang et al., 2012; Mitev & Venters, 2009).

While benefiting from an accuracy of research topic and broader interest in results, transdisciplinary research also puts strain on the research process, on workload, and the possibilities for achieving scientific credits (Berker & Bharathi, 2012; Lang et al., 2012). The management of the project can be a puzzle. The researchers will find themselves in new roles for which they are not appropriately trained (Wittmayer & Schäpke, 2014). They will need to deal with tensions that can arise between participants and assume a role of knowledge broker or facilitator. These new roles need time and resources to develop skills. Wittmayer and Schäpke (2014) argue that "institutional space" is needed from the universities and from funding agencies to support researchers in their production of scientific publications as well as their handling of processes to improve the societal relevance of results. Lack of time and resources for organizations to engage in the transdisciplinary projects can hinder the co-production of knowledge, but also individual's (non-)willingness to adapt and share knowledge (Gluch et al., 2013). Another inhibiting factor is discontinuous participation among staff of collaborating companies and organizations change workplace (Lang et al., 2012). In their study of an arena in the built environment, Gluch, Johansson, and Räisänen (2013) found that the motivation to share knowledge is related to each individual participant's expectation of, and invested interest in, arena activities.

Experiences from Five Projects

Five cases of transdisciplinary research illustrate practical experiences with this form of research. The selection reflects differences in size, funding, and approach of the projects (Table 1). At the same time, they demonstrate a chronological development of working with transdisciplinary research through consecutive projects.

Demo 04/06 – Demonstration Projects for Sustainable Building

Aim and approach: These first two transdisciplinary projects followed a tradition of engaging in action research in the Department of Architecture at Chalmers University of Technology in Gothenburg, Sweden. They were motivated by an observed gap of innovation from demonstration projects to mainstream sustainable building (Femenías, 2004). The objective for Demo 04/06 was to further understand but also support innovation in sustainable building by sustaining a knowledge-sharing arena around six ongoing frontline demonstration projects for sustainable building (Rubino, 2006). Developers, architects, and technical consultants engaged in these projects met 3 to 4 times a year to discuss problems and experiences. The explorative arena was designed and led by the researchers. At times, the arena was opened up to external participants. Connected to the arena, there were change agents, actors, and organizations identified as possible agents to diffuse knowledge outside the arena.

Learnings and innovation: The arena was appreciated and well-attended by collaborating as well as external companies. Sustainable building was still in its infancy, and practical experiences and built examples earned much attention. However, the good results from the demonstration projects were not diffused and, even more important, they were seldom taken up by the organizations that were involved in them. Demonstration projects continued to be one-off investments without any larger impact on the industry. The project analyzed a number of inhibiting factors based on socio-technical transformation theory (Rubino, 2009).

The legacy of these first projects is the building of trust and relations with a local network of industry partners. This has been an important foundation for new collaborations and transdisciplinary projects.

Outcomes: The project led to a PhD thesis (Rubino 2009) and to a number of other scientific papers (Eden et al., 2005; Femenías, 2005; Femenías et al., 2008). The projects also resulted in a guidebook, which was a kind of hypothesis for an improved innovation process among construction clients (Femenías, 2009).

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Table 1. Information about the five transdisciplinary research projects carried out from 2004–2018

Project	Aim	Size	Budget
Demo 04/06 2004–2009	Understand and support knowledge transfer between demonstration projects	Medium 20–30 participants evolving around 6 case projects: 1 academic institution and 1 academic discipline; 15 public and private organizations	Phase 1 (04): 1.10M SEK (~$160K CAD) research funding Phase 2 (06): 3.17M SEK (~$450K CAD) research funding
3iii 2009–2013	Understand and support innovation processes in client organizations	Small 8–10 participants: 1 academic institution with 2 academic disciplines; 1 national public client organizations; 2 municipal client organizations	2.20M SEK (~$315K CAD) research funding 2.36M SEK (~$340K CAD) in in-kind and 600K SEK (~$85K CAD) in effective as co-finance Request: minimum of 50% co-finance of which 20% in ready money
ReBo 2010–2012	Define and support integrated sustainable renovation	Medium 20–30 participants evolving around 3 case projects: 1 academic institutions with 4 disciplines; 13 private and public organizations/companies	2.46M SEK (~$350K CAD) research funding 2.50M SEK (~$360K CAD) in-kind co-finance Request: 50% co-finance
STED 2016–2018	Develop and support uptake of digital tools for sustainable design	Medium 12–15 participants: 4 academic institutions with 2 disciplines; 5 architect offices in the Nordic Countries	1.20M NOK (~$190K CAD) research funding 1.20M NOK (~$190K CAD) in-kind co-finance Request: 50% co-finance
SIRen 2014–2018	Develop tools, share knowledge, and support innovation for sustainable integrated renovation	Large >50 participants: 10 academic institutions and 5 disciplines; 21 private and public companies and organizations	23M SEK (~$3.3M CAD) research funding 23M SEK (~$3.3M CAD) in-kind co-finance Request from funder: 50% co-finance

3iii – Initiating and Implementing Innovation for Sustainable Building

Aim and approach: As a result of the lack of innovation for sustainable building, 3iii was initiated with the specific aim to understand innovation processes in client organizations, which is a key actor to innovate for sustainable building. 3iii engaged a small number of participants, a few of whom had established connections with common interest from Demo04/06. The project and the arena were driven by the academic actors and focused mainly on description and knowledge-first. The project was encircled around project workshops and traditional descriptive studies of the organizations involved, their innovation systems, and a smaller number of sustainable building projects.

Learnings and innovation: The project experienced problems with trust between the academic institution and some of the partners. A particular challenge was that one of the collaborating partners underwent a larger re-organization during the project. Also, the employee from that organization that initially discussed the participation in the project retired before the project started. The search for replacement employees delayed the project start by almost six months. Furthermore, the new employees joined the project mainly out of obligation, and they expressed a lack of interest and almost distrust towards the aim and the leadership of the project. At that time, all municipal organizations in the city experienced internal investigations to fight corruption, which could also explain their opposition to studies of their internal processes.

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Equally, in one of the other participating organizations, some employees were rather unwilling to provide data. This could be explained by the challenge that the responsible participant had in generating interest and trust for the research projects among other employees in their organization. In later stages, a conflict arose between the researchers and the "implementation agent", a role assigned to one industry participant by the funding agency to ensure the implementation of results from the research project.

Over the course of the project, the participating client organizations did achieve some successful innovations in sustainable building. Although the motivation to adopt and implement innovations had been enhanced, new problems were detected and studied such as the gap between planned and evaluated energy efficiency.

Outcomes: The project has been presented in scientific papers (Bougrain & Femenías, 2016; Femenías et al., 2009; Femenías & Kadefors, 2011), a scholarly book chapter (Bougrain & Femenías 2017), a popular science book chapter (Kadefors & Femenías, 2012), and in a new guideline for systematic innovation in client organizations (Kadefors & Femenías, 2014). Over 300 copies of the guidelines were distributed, and the content was presented during several well-attended seminars.

ReBo – Strategies for Integrated Sustainable Renovation

Aim and approach: The aim of this project was to frame problems of sustainable renovation through development of strategies to support decision making for sustainable renovation of multi-residential buildings from the Swedish pre-boom "Folkhem" period (~1940–1960). The point of departure was to weigh environmental performance, energy efficiency, and cost-effectiveness with cultural, historical, architectural, and social values when making decisions about building renovations and alterations. A further aim was knowledge sharing.

Inspired by the arena concept, successfully developed and applied in the Demo 04/06 project, the ReBo project focused on knowledge and innovation on sustainable renovation by gathering partners from industry and the public sector (Thuvander et al., 2011) using the arena model.

Experiences: The ReBo project was mainly process-oriented and the large group of practitioners meet for discussions, workshops, and common study trips (Figure 1). Without having consulted practical literature on transdisciplinary research, which was scarce at the time, ReBo naturally followed the three steps later described by Lang and co-authors (2012). Initially, the researchers stepped back and let the arena develop a common understanding of the problem. One of the results was that participants in the arena decided after several meetings to complement the expertise in the group by inviting the Swedish tenants association to participate.

The first phase became rather long and unfocused until the group decided to centre the discussions around a few real cases of renovation, which the property owners in the group were planning for. At the same time as this was a way forward, it also split up the arena. In the second phase, work was carried out in smaller groups encircling some of the property owners and their real cases. One of these sub-projects was successful in creating a boundary object, a process matrix for integrated sustainable renovation, which made the subject more tangible for all involved (Thuvander et al., 2013).

The project met a few challenges. As in the previous projects, there was a discontinuity of participants as individual employees from participating organizations were replaced during the course of the project. The researchers also underestimated the importance of informing the new participants about the specificity of the process-oriented and non-hierarchical transdisciplinary project set-up. A new participant, for whom this kind of transdisciplinary project was unfamiliar, questioned the approach and asked the researchers to take stronger leadership of the process. This event created a bit of a confusion in the arena, and even made the researchers start to question their approach and outline for the project.

Figure 1. Workshop in the Rebo project 2011, held in a bus during a study trip

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The project also suffered from a confusion between a "real" renovation project, which engaged other consultants not involved in the research, and the parallel "shadow" (i.e., non-paid) investigations in the ReBo arena. The fuzzy delimitation between the research project and the real renovation projects also affected the innovation processes as practical and economic aspects, upheld by the property owners, ruled out even the theoretical investigation of new innovative solutions and strategies.

Learnings and innovation: The ReBo project was an eye opener for participants about the complexity of this kind of sustainable renovation, as indicated in the opening quotation of this article. However, the project also resulted in some concrete knowledge production and innovation. A process matrix developed in the later phases of the project (Thuvander et al., 2014) was later on used by the property owner that was involved in its development. However, the matrix was of less practical value for the other industry partners in the arena. The process matrix was further developed in two new transdisciplinary research projects, SIRen and STED, as described below.

Outcomes: The project resulted in scientific papers (Femenías et al., 2013; Thuvander et al., 2011; Thuvander et al., 2012; Thuvander et al., 2013), reports (Danielsson et al., 2014; Thuvander & Femenías, 2014), and a book chapter (Thuvander, 2015). Some reports, conference papers (Ottoson & Thuvander, 2013; Ottosson et al., 2014), and a popular science article (Thuvander, et al., 2014) were co-authored with industry partners. The project also held a number of public outreach seminars with good attendance.

STED – Sustainability Tools for Environmental Design

Aim and approach: The aim was to develop and support innovation of digital tools for sustainable architectural design focusing on new construction, as well as renovation and transformation. The main aims were: 1) to develop innovative generalizable system design solutions; (2) to create innovative design methods using ICT for decision support combining energy efficiency, environmental design, and lifecycle thinking; and 3) to boost knowledge creation by creating a Nordic Innovation platform. STED, the only international project presented here, involving partners from five Nordic countries, each co-funding 50% of the project costs.

The knowledge-sharing arena met twice a year, and in between, three academic partners from Denmark, Sweden, and Norway engaged in knowledge production with the five architect offices in Sweden, Norway, Denmark, Finland, and Iceland. In most cases, students were involved by working in design studios or doing a master's thesis.

Learnings and innovation: The knowledge-sharing arena had the function of a discussion group with open and vivid discussions. The participants from academia acted as knowledge mediators but also saw the richness of knowledge that exists at the offices and the challenges to integrating it. Not all of the involved architects were enthusiastic about testing digital tools, something which enriched the discussions in the arena, as provocative questions had to be dealt with.

The work with specific cases allowed the architectural offices to test new ideas together with students and academic staff. In one of the cases, a real design proposal was built; in another case, new digital assessment tools were developed and implemented in the architectural firm's design process.

The common workshops and the push from the researchers to test innovative digital tools resulted in one office setting up a new R&D position at the office.

Outcomes: The project produced a large number of master's theses and some scientific publications, which are all summarized in a co-authored popular science book (Jensen, 2018). A final seminar book release attracted an audience of nearly 100 participants in Denmark, which also points to a broader interest and the potential applicability of the results.

SIRen – Sustainable Integrated Renovation

Aim and approach: SIRen is funded as a strong research environment connecting different disciplines (civil engineering, architecture, economy, sociology, heritage studies, etc.) from 10 universities and research institutes with over 30 building sector actors (property owners, consultants, contractors, etc.), governmental authorities, regional, and municipal agencies, and other non-governmental organizations. The aims are to develop and share knowledge and support innovation in sustainable renovation and to support innovation in renovation. The larger arena meets twice a year while small sub-groups have been formed to carry out both knowledge-first and more process-oriented projects, notably in connection to four real-world innovation laboratories (Mjörnell et al., 2015).

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Learnings and innovation: The strength of this large project is that it connects multiple disciplines and companies and can focus on a large variety of aspects of sustainable renovation. The challenge is to keep up the interest of all parties, including both academia and industry. Some participants have dropped off due to other priorities and because they perhaps did not manage to connect to some of the main activities in the arena. As in the other projects described, the replacement of employees from engaged organizations is also a challenge in this project.

The project is still ongoing, and the aim is to deliver a process model to support sustainable renovation. Parts of this model have already been tested in the real-world laboratories with good results (Femenías et al., 2017; Stenberg, 2015).

A recent survey among participants received more than 40 responses (Mjörnell, work in progress) that reveal the value of the arena for networking, collaboration, and knowledge exchange, as the following examples illustrate:

- *"Get in touch with people whom I otherwise would not have met in such favourable circumstances."*
- *"Plenty of time for discussion."*
- *"Get in touch with others with similar research opportunities that you can make joint applications with."*
- *"The network as a whole and the composition as 'all' parts of the construction process are included, from major contractors to individual consulting companies, from national authority to municipality."*

Outcome: The project has resulted in a large number of scientific and popular science publications co-authored with the academic, industry, and public authorities and agencies. For a list of publication visit: renoverings centrum.lth.se/siren/. The project has had a wide outreach and has been presented widely nationally but also internationally. The project is connected to two national knowledge centres: the National Center for Renovation and the National Center for Sustainable Building.

Discussion

The presented cases confirm many of the earlier reported experiences with transdisciplinary projects. The ReBo project follows the outline of transdisciplinary research as described by Lang and co-authors (2012), without knowledge of these definitions. All projects involve elements of knowledge-first and of process-orientation (Miller, 2013; Wittmayer & Schäpke, 2014), thus adding to the evidence that Mode 1 and Mode 2 research partly overlap (Bresnen & Burell, 2013; Ziman, 1996). All of the projects were academia-driven, but to varying degrees. The 3iii project was more of a knowledge-first project and was led by the academic institution, something which led to collaboration problems with the partners. As already stated by Gluch and colleagues (2013), there is a risk that a too scientific approach, a "science push", can lead to disinterest among participants.

ReBo and STED were more process-oriented. The ReBo project experienced a lack of legitimacy for the research approach and the project management among industry partners, which is a common challenge for this type of project (Wittmayer & Schäpke, 2014). STED was at times weighed down by long discussions. The non-hierarchical knowledge production upheld in theory (Balsiger, 2004) can be difficult to reproduce in reality as this can lead to unfocused and long discussions. Transdisciplinary projects can also lead to conflicts when existing institutions and hierarchies are devalued (Berker & Bharathis, 2012). The experiences from 3iii most likely illustrate a suspicion that academic knowledge is inadequate for use in practice, as upheld by Argument and co-authors (1998).

In the following subsections, we highlight two aspects that we found are of major importance for developing knowledge and innovation through transdisciplinary projects. First, it is important to "maintain the space", which means to keep up the interest and the participation in the arena, otherwise the project will only be a Mode 1 project. Second, transdisciplinary projects take time. This second aspect is something that has been brought up by earlier literature in the field (e.g., Argument et al., 1998; Deprés et al., 2004; Gluch et al., 2014). However, in contrast to earlier literature that has focused on experiences from single transdisciplinary projects, we bring forward the meta-learning and innovation process built up by consecutive projects over a longer period.

Maintaining the space

One of the main challenges with transdisciplinary projects is to establish and maintain the process arena. As stated by Lang and co-authors (2012), it is important to have the right level and scale of participation. The participation should be manageable and maintained throughout the project. Although it can be argued that

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the projects are not long enough for knowledge production and the development of common language and cultures, they still take several years. Industry often works with shorter timeframes, and the transdisciplinary project participation is often disrupted as employees tend to change position in the company or employer.

Thus, it is important to establish a common understanding of both the problem and aim of the project. Boundary objects are useful; they can be concepts or definitions that make the discussion tangible at the same time as they are open for further interpretations. Our results show that, to maintain the arena and reach the best collaborations and innovations, it can help to focus on concrete cases or tasks and in smaller constellations. This is usually done by making sub-groups within a larger arena project (ReBo and SIRen) when entering the knowledge creation phase, that is, in phase two according to Lang and co-authors (2012). The motivation for knowledge sharing is related to an active participation (Gluch et al., 2013). At the same time, making subgroups will challenge the validity and legitimacy in the larger arena, and consequently the broader up-take, of the innovation. If the project consists of a small number of academics and many other stakeholders, making smaller sub-groups focusing on topics that interest all participants might overload the academics with work.

Maintaining the process arena will also be a question of resources among the participating stakeholders. Large companies are typically better able to pay for their employees to actively participate than small companies. In order to engage smaller-scale technical consultants and architect offices, it helps if they can be paid through the research funding. However, even if the organization and company have the resources to pay, their employees still need to be able to set aside other tasks so they are free to engage in the project. It is therefore better for the company if their immediate tasks correlate with the those of the research projects.

It takes time

Time is a crucial factor in transdisciplinary projects. For example, companies seek short-term solutions and results (and also need these to motivate their active engagement in a transdisciplinary project), whereas academic knowledge production takes time (Argument et al., 1998). The development of common cultures and perspectives, which are necessary to establish collaboration in the arenas, is also something that takes time (Gluch et al., 2013) and requires frequent meetings (Deprés et al., 2004).

Wittmayer and Schäpke (2014) argue for an "institutional space" provided by the university to support researchers with the extra time needed for facilitating the arena and for scientific publication. Our experience is that, even if scientific publication can be produced with the results from transdisciplinary projects, time is taken from scientific publication in order to maintain the arena, and also to produce reports and guides for the participating stakeholders. A further challenge, as we have experienced in Sweden, is that project reports typically must be produced in the local language, whereas the scientific publications typically must be in English.

The empirical material in this study shows how several transdisciplinary projects connect together. This has provided a continuous learning process that might be an alternative to the "institutional space", which the university might have difficulties in financing. Through these consecutive projects, a network with common problems and perspectives has been generated. Results as well as working methods from one project have been taken into the next project (Figure 2). For example, preliminary results and theory on innovation processes developed in Demo04/06 were tested and further developed in 3iii, and were later on used in STED. Furthermore, the process matrix for integrated sustainable renovation developed in Rebo has been used in SIRen and in the STED project.

This continuity has helped the building up of sustainable networks. One of the architect firms participated in four of the presented projects but with different employees and varying competences (e.g., environmental specialist, designer, and social expert). Some of the other companies joined two of the presented projects. Most of the industry partners joined Rebo and later on SIRen which both focus on renovation (Figure 3). The established networks, in which common understanding of problems, have been an advantage when engaging the same organization in new projects.

Finally, as discussed by Lang and co-authors (2012), outcomes from transdisciplinary projects are not only tools, projects, or processes. Personal insights also result, as expressed by a participant in the ReBo project in the opening quotation for this article: *"We had the technical part ready but realized that this was the simple part of the challenge."* Our experience is that the personal insights from discussions in the process area is an important outcome and highly valuable for academics and other participants. However, as shown by 3iii

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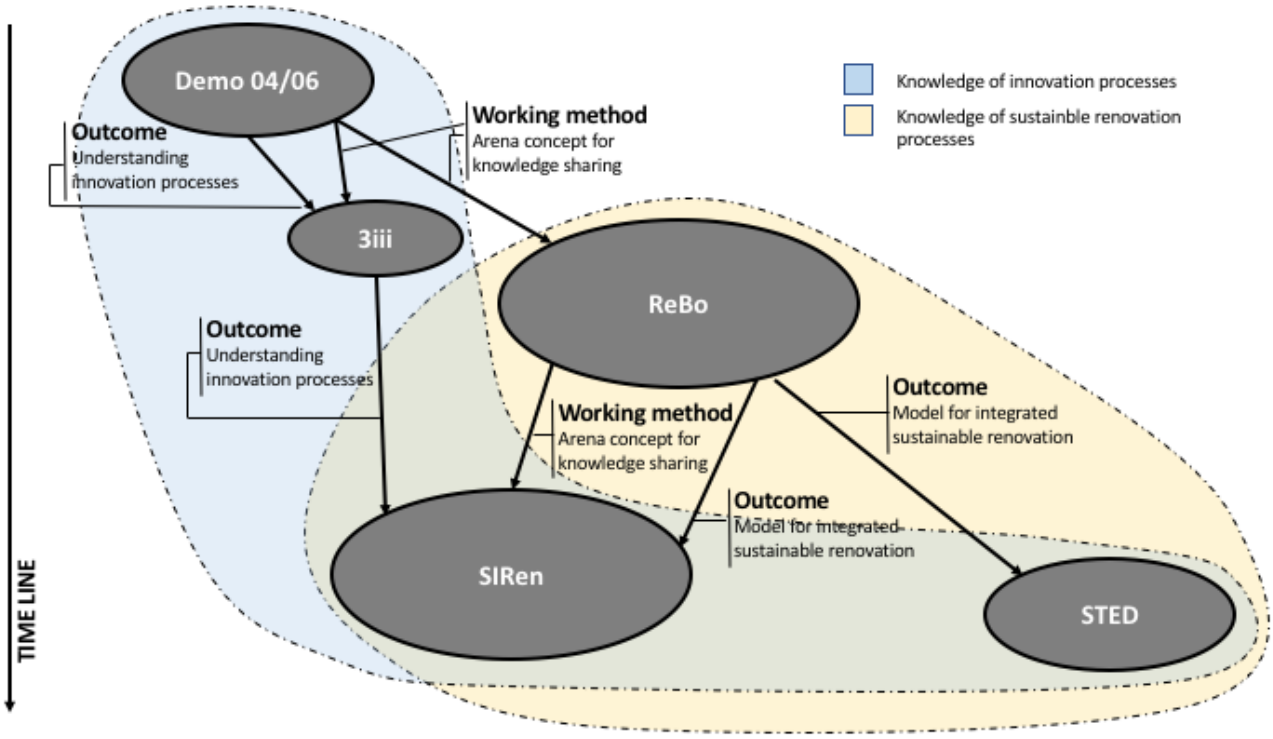

Figure 2. Relationship and knowledge flows between the five transdisciplinary projects

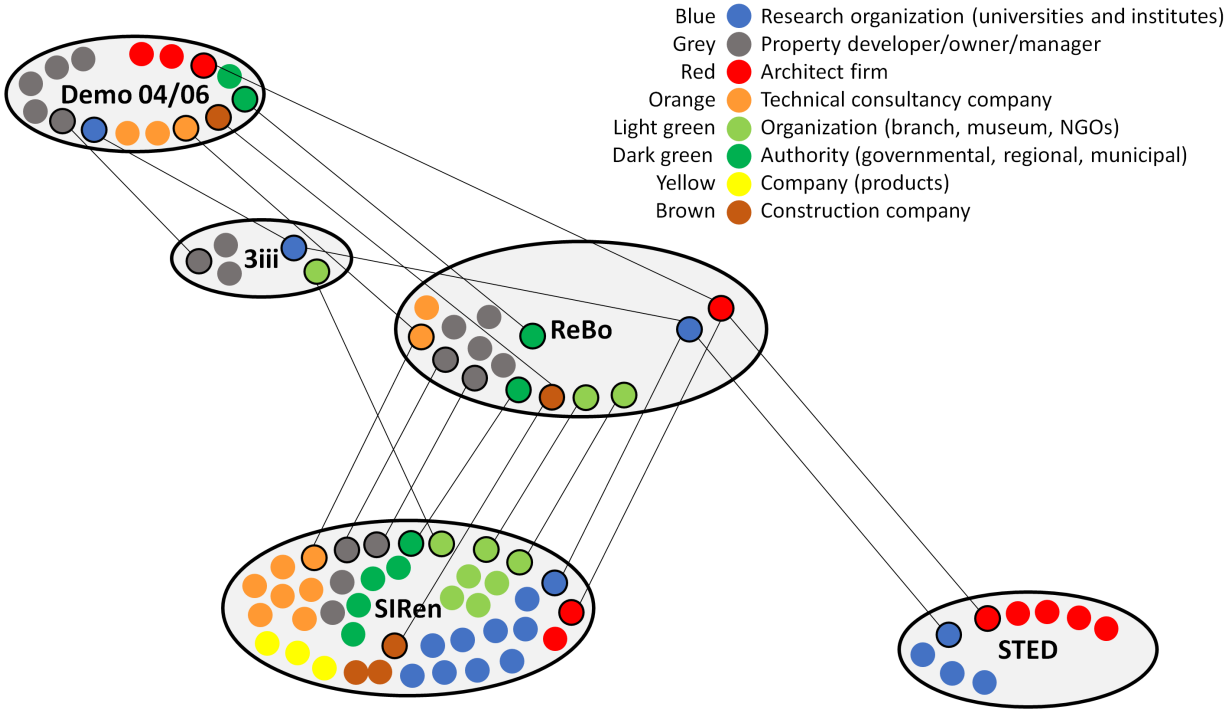

Figure 3. The actor network representing the participating organizations in the five transdisciplinary projects and highlighting organizations that have been involved in two or more projects. One dot represents one participating organization and the different colours represent different types of participating organizations.

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and ReBo, for example, these projects have also resulted in more direct support for innovations such as tools for sustainable renovation that have been put into practice.

Conclusions

Transdisciplinary research offers many opportunities, but it also involves many challenges. One of the most important experiences we wish to transmit is the importance of time. It takes time to build up networks, trust, and common perspectives. But, it also takes time to develop knowledge and innovation. Often, one project is too short, and we would advocate for planning for continuous projects to reach sustainable results.

Our practical suggestions for others wishing to engage in transdisciplinary research are:

- Read literature with theoretical definitions as well as practical experiences and guidelines for how to carry out a transdisciplinary project. Summarize important points in a project set-up document.
- Establish an arena with interested partners with competences that you think are useful, and keep the door open for the addition of more partners and competences to join.
- Plan for how to maintain the larger arena and the interest over time. Frequent meetings are needed, especially in the initial phases, in order to define common problem views and aims.
- Describe common aims, the approach and leadership of transdisciplinary research, rules of conduct, as well as expectations of each participant, which should be made available to all initial participants and newcomers during the whole project.
- If you establish a larger national arena, local sub-projects are needed for focused work in parallel with common activities in the larger group. Search for boundary objects (e.g., definitions, frameworks, models) that make the discussions tangible while still open for interpretations.
- In order to reach actionable and usable knowledge and innovation, it helps to focus work around real problems or cases, ideally in smaller groups.
- Search for opportunities to actively engage the participation of industry and public actors (in terms of time and financial resources), especially if they should be part of an innovation process.
- Share the workload: if possible, encourage non-academic partners to write case reports or popular trade articles, or to co-author articles.
- Make sure to establish a good network with possibilities for consecutive projects in order to further develop common understandings and innovation.

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Transdisciplinarity at the Crossroads: Nurturing Individual and Collective Learning

Chris Riedy, Dena Fam, Katie Ross, and Cynthia Mitchell

> *"At each point in our lives, we are at a crossroads. We are the fruit of our past and we are the architects of our future... If you want to know your past, look at your present circumstances. If you want to know your future, look at what is in your mind."*
>
> Matthieu Ricard
> Scientist and Buddhist monk

Practitioners of transdisciplinary inquiry, which we define to include research, learning, collaboration, and action, encounter innumerable tensions. Some tensions are universal, while others are unique to that particular inquiry at that point in time. Resolving these tensions requires innovative practices, which emerge through experience with transdisciplinary inquiry. In this article, we reflect on two decades of transdisciplinary inquiry at the Institute for Sustainable Futures. Drawing on that experience, we argue that one crucial innovative practice is to create space for collective, reflective learning. Such learning frequently takes place in spaces we call "crossroads". These are formal and informal spaces where practitioners who have been on their own transdisciplinary learning journeys (experiencing diverse tensions and applying diverse approaches) come together in dialogue to share, reflect, critically and constructively question, imagine, challenge, and synthesize their experiences into collective organizational learning. Crossroads can emerge spontaneously but can also be consciously nurtured. In our experience, they help us to sustain the innovation needed for transdisciplinary inquiry and to avoid stagnation or routinization. At these reflective, and often times transformative, crossroads, we make sense of our messy, non-linear transdisciplinary journeys and develop innovations to take our transdisciplinary practices forward.

Introduction

Practitioners of transdisciplinary inquiry encounter innumerable tensions. Some tensions are universal, while others are unique to that particular inquiry at that point in time. Some would be familiar to all researchers, while others are specific to transdisciplinary inquiry. Perhaps the most familiar of the latter is the trade-off between breadth and depth of research that must be navigated when moving beyond disciplinary boundaries. There are no agreed rules or conventions for resolving such tensions. Instead, practitioners of transdisciplinary inquiry draw on their experience to develop and test innovative responses to tensions that arise in their context. Given the lack of fixed rules for resolving transdisciplinary tensions, there is much to gain from creating spaces to share these innovations and their outcomes. In this article, we reflect on two decades of transdisciplinary inquiry at the Institute for Sustainable Futures (ISF; tinyurl.com/yczatd9g), focusing particularly on the spaces we have created to share our experiences with each other.

The authors of this article are all researchers at ISF. Established by the University of Technology Sydney (UTS) in 1997, ISF is a transdisciplinary research institute with a mission to create change towards sustainable futures. From the outset, ISF brought together researchers and practitioners from diverse disciplines to tackle wicked problems (Rittel & Webber, 1973) such as climate change, international development, resource scarcity, and social justice. Since the earliest days of ISF, we have conceptualized and described our research as transdisciplinary. Our recent contributions to transdisciplinary theory and practice include Mitchell et al. (2015), Fam et al. (2017), and Fam et al. (2018).

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Our transdisciplinary approach is underpinned by several nested communities of practice (Wenger, 1998, 2010). At a small scale, our researchers form project teams to engage in specific research projects, typically in close collaboration with stakeholders from government, business, or civil society. Membership of these project teams is fluid, shifting with each new project to meet changing research objectives. At a larger scale, ISF has ten research areas:

1. **Cities and buildings:** Improving the liveability of urban environments with holistic and net-positive social, infrastructure and resource solutions.

2. **Climate change and adaptation:** Helping partners adapt to the challenges of a changing climate.

3. **Food systems:** Transforming food systems to ensure healthy, thriving, and food-secure communities and businesses.

4. **Energy futures:** Accelerating the transition to more decentralized energy systems that are clean, affordable, reliable, and empower communities.

5. **International development:** Working in partnerships to end poverty and ensure sustainable development for all.

6. **Landscapes and ecosystems:** Enhancing ecosystem integrity and livelihoods by incorporating perceptions, values, and practices into decision making.

7. **Learning and social change:** Facilitating individual, social, and organizational transformation, learning, and change.

8. **Resource futures:** Advancing responsible and efficient production and consumption by fostering stewardship and circular resource flows.

9. **Water futures:** Developing restorative, sustainable, and resilient water management solutions.

10. **Transport:** Providing solutions for quality transport services that maximize productivity at least cost and lowest impact.

Although membership of these research areas is not fixed, they are more stable than project teams and provide a space for ongoing learning and reflection on project experiences related to the research area in question. These research areas meet regularly and these meetings provide one space for transdisciplinary practice to develop, bounded by problem spaces rather than disciplines.

At a still larger scale, ISF operates a graduate research program, providing research training to masters and doctoral students and postdoctoral fellows. Again, membership changes as students move through the program, but the program provides a relatively stable reflective space for approximately 45 students and their supervisors. In addition to individuals, project teams, research areas, and the graduate research program, ISF as a whole also provides space for collective reflection through planning days, regular informal presentations and dialogues, and staff meetings.

Although there is no consensus even within ISF on what constitutes a transdisciplinary approach, we believe that it is:

- **Purposive:** positive change within a wicked situation is an explicit goal of the research.

- **Holistic:** it engages with the past, present, and future of whole systems and transgresses disciplinary and governance boundaries.

- **Participatory:** given that diverse stakeholder perspectives (beyond academia) are necessary to achieve progress on wicked problems, it allows us to see more of the whole picture and encourage ownership of, and equitable benefit from, responses.

- **Innovative and experimental:** it enables testing of ideas through real-world interventions and action research.

- **Dynamic:** the research plan adapts to the changing context and new knowledge.

A transdisciplinary inquiry involves more than research; it is an integrated process of research, learning, collaboration, and action. It incorporates cycles of action and practice that inform research and theory development, which in turn inform new practice. These cycles are connected by a constant process of reflection and sensemaking that supports innovation and deepens both theory and practice.

Our engagement with transdisciplinary approaches over the past 20 years has been an ongoing "learning

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journey" (Crick, 2007) with many twists and turns, propelled by the exploratory work of our cohort of postgraduate research students and the action research of our academic staff. Writing about the learning journey metaphor, Crick (2007) depicts the learner as "a person, with a sense of self, identity and intention, who has an objective or an outcome in mind, and who moves through a particular domain, engaging in inter- and intra-personal learning practices along the way". Each person, project team, and research area at ISF regularly undergo markedly different learning journeys as they engage in applied transdisciplinary inquiry. Learning journeys are diverse due to the unique:

- topic, scale, or location of the research.
- composition, capacities, experience, and dynamics of the internal and external team.
- methodologies created and blended for scoping, probing, inquiring, sensing, meaning-making, analysis, synthesis, emergence, communicating, and embedding the research.

Considering that ISF has over 80 staff, 45 graduate research students, 400 projects per year and 10 research areas, working across Australia and internationally, we experience great diversity in individual and team learning about transdisciplinary inquiry. We have learned that transdisciplinary inquiry is characterized by diverse tensions or challenges, experienced differently by different individuals and teams. For example, transdisciplinary inquiry may need to:

- pause to take the time required for appropriate methodologies to emerge from and for the unique conditions of the project (Meadows, 2008).
- justify its value, when the types of outputs of transdisciplinary research are valued differently to those produced by Mode 1 science (Gibbons et al., 1994; Mitchell et al., 2015).
- collectively explore fluid yet guiding boundaries (Midgley, 2000).
- collaboratively reorient the goals of the research toward meaningful aims yet allow for emergence (Brown & Lambert, 2012).
- speak, interact, and integrate across disciplinary boundaries and worldviews, while maintaining the depth of the disciplines (Mitchell & Ross, 2017).
- engage at the paradigmatic (Ross & Mitchell, 2018) and worldview (de la Sienra, 2018) levels, while also being pragmatic.
- create meaningful dialogue in an ongoing way and generate genuine trust while engaging with challenging questions of power and ownership.
- provide space for individual agency while working towards a shared goal (Freeth et al., 2019).
- build capacity and capability for clients and collaborators to value the processes of and insights from transdisciplinary approaches.
- reformulate contractual models to allow for flexibility in specific project deliverables.
- devote time for long-term, well-funded transdisciplinary projects, while recognizing that many funders are not seeking this type of approach.

Although the authors cited above, and others, have written much about these challenges and unexpected perturbances, the important point is that we are still, and perhaps always will be, collectively learning how best to resolve them. There is much to learn from sharing diverse individual and team innovation that emerges in response to them. Therefore, learning is central to our definition of transdisciplinary research and practice: it underpins innovation and catalyzes organizational and social change (Colvin et al., 2014). Further, the type of learning required to resolve the tensions identified above is often transformative. Transformative learning involves "a deep shift in perspective, leading to more open, more permeable, and better-justified meaning perspectives" (Cranton & Taylor, 2012). Such learning is frequently needed if we are to fully see tensions in transdisciplinary inquiry and find innovative pathways through them.

In this article, we reflect on how ISF achieves collective, and often transformative, learning through sharing, discussing and reflecting on our diverse individual and team learning journeys. There are two important aspects to this collective learning. First, we need to give our researchers sufficient freedom and agency to cultivate distinct, individual learning journeys, take risks, and develop innovative transdisciplinary inquiries. Second, we need to create or support intersection points for collective, organizational learning. These intersection points, or "crossroads", are places of innovation where habitual ways of seeing the world are challenged and

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new ideas emerge. It is these crossroads that are the focus of this article. The relationship between learning journeys and crossroads is shown conceptually in Figure 1.

Transdisciplinary Crossroads at the Institute for Sustainable Futures

In reflecting on where innovation happens in our collective transdisciplinary practice, the metaphors of "learning journeys" (Crick, 2007) and "crossroads" emerged. In our research projects, we are constantly learning about the context and process of transdisciplinarity, and different ways to respond to the tensions and challenges identified earlier. The unique and particular history of individual researchers as they work on diverse research projects creates a distinct learning journey, which is defined by the experiences they have, the thinking they do, the perspectives they are exposed to, and the practices they employ to make sense of these experiences. This individual learning journey contributes to our particular worldviews and assumptions about transdisciplinary inquiry (i.e., research, learning, collaboration, and action).

We have found that creating collective spaces where individuals can come together and reflect on their individual learning journeys is crucial to ISF's transdisciplinary practice for two reasons. First, sharing experiences is itself a valuable source of learning for ISF as an organization. Being exposed to situations others have experienced, including alternative forms of transdisciplinary practice, adds to our own experience and may trigger ideas that we can apply in our own research projects or warn against particular approaches. For example, one of the authors tested an idea for rapidly establishing transdisciplinary research teams through an intensive workshop process inspired by social innovation labs (Westley et al., 2012) and found it was not possible to short-circuit the lengthy trust-building and dialogue process that typically characterizes the start of a transdisciplinary research project. Sharing this experience, in this case through a collective writing project, helps others to avoid going down a similarly unproductive path. Second, reports from other learning journeys may challenge aspects of our individual practice that have become rigid and may be stifling innovation.

We can think of these spaces where individual learning journeys intersect with collective learning as "crossroads". These crossroads can emerge organically, through spontaneous conversation. However, there is also a role for purposefully creating and nurturing such spaces to support a transdisciplinary practice. We build such spaces into our projects but also create them at larger scales through research area meetings, postgraduate retreats, informal seminars, and writing projects. There is overlap between the notion of a crossroads and

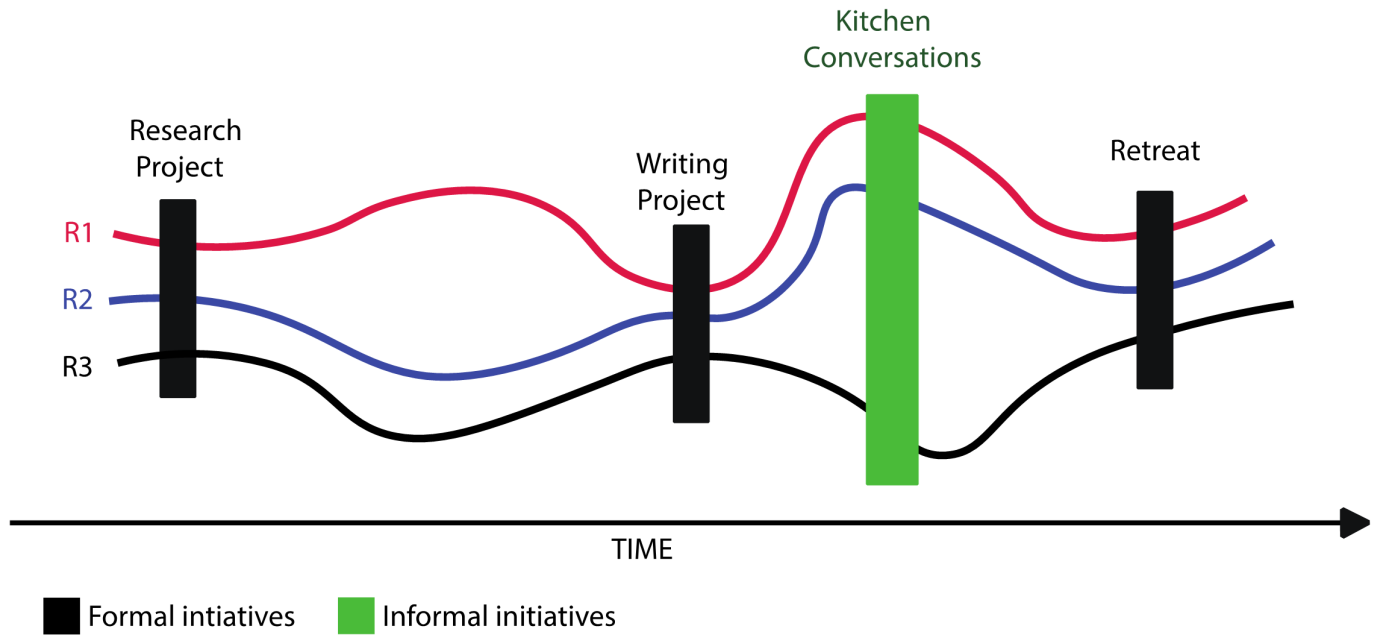

Figure 1. Learning journeys and crossroads

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Wenger's (1998, 2010) concept of a community of practice, however crossroads can be more ephemeral and transitory. A fleeting conversation in the corridor is not a community of practice, but it can act as a crossroads where learning takes place. At these crossroads, different worldviews come together and can clash or resonate. These worldview interactions can trigger learning and innovation. Several examples of crossroads are described below.

Crossroads Example 1: Collective Writing

One of the authors spent time helping a teaching institute in New Zealand that had little transdisciplinary experience to establish a new transdisciplinary research master's degree. The experience is documented in Riedy (2016). To help with teaching transdisciplinary practice to program staff and supervisors, he developed and used some simple definitions of transdisciplinary research which then became embedded in his own worldview of what transdisciplinary research is. In essence, he came to think that anything that did not continuously involve non-academic participants at all stages could not be called transdisciplinary research. He documented this position in an early draft of a chapter for a book edited by current and former ISF staff.

Upon reviewing the book chapter, one of the other editors pointed out the rigidity of a definition of transdisciplinary research that is not willing to compromise at all on involvement of stakeholders. Such a definition fails to recognize the inevitable trade-offs and tensions that happen in practice. For example, there are stages of the research process that stakeholders are less interested in, and there is always a balance to strike between opportunities for participation and the other constraints on stakeholder time. For the author, the collective writing project acted as a crossroads where he learned to let go of a rigid definition and be more flexible in balancing the tensions associated with stakeholder involvement. This led to innovations in his practice for working with stakeholders. For example, he designed a research project on cohousing for older people that envisaged stakeholder involvement using concentric rings – a closely involved inner ring (Steering Group) that met monthly, a supportive middle ring (Advisory Group) that met quarterly, and an outer ring of participants that often had only a single touch point with the project. This proved highly effective.

Crossroads Example 2: The Annual Graduate Research Retreat

A two-day annual residential retreat for research students and their supervisors is a key space for collective learning at the intersection of theory and practice. Our first annual retreat was held in 2002. Before each retreat, participants engage in the design and planning of the program to meet current collective learning needs. At the retreat, supervisors and students deliver or participate in facilitated sessions. Examples include defining transdisciplinary research, change creation models, systems thinking tools and methods, theories of change, writing and publishing tips and tricks, and epistemological stance. There is typically a mix of sessions requiring deep theoretical engagement oriented towards enabling shared conceptual leaps and time for reflection on how these leaps might manifest in students' and supervisors' research activities, as well as sessions more focused on practical "tips and tricks" for graduate research.

Riedy and co-authors (2018) explored the way in which our annual retreat functions as a community of practice. In the current article, our focus is on its role as a crossroads for collective learning. Graduate research students (and their supervisors) embark on learning journeys that, by definition, take them into new territory; their work must be original and innovative. When those students engage with diverse disciplines, as they do at ISF, a transdisciplinary practice can be greatly enriched by sharing innovations from these journeys. While there are many places where such sharing can take place, holding a collective annual space open to all has been crucial to our evolving transdisciplinary practice.

At this crossroads, where individual learning journeys intersect, something new often emerges. We use the phrase "Aha! moment" to capture the feeling of breakthrough and innovation that can arise from our engagement with each other. An "Aha! moment" can be individual or collective. Exposed to other perspectives, individuals form new insights that they carry back to their individual journeys. These insights can take many forms – new knowledge, new theories, new practices, new questions. Collectively, we find that creating a space for engagement with a common question or challenge leads to conceptual leaps forward that later become embedded in our own transdisciplinary practice. Many of these conceptual innovations now form the

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canon of our graduate research program, passed on to new students in annual workshops, but developed for the first time at retreats. It should be no surprise then that we recommend setting aside an annual protected space for transdisciplinary engagement – a formal crossroads – as the centrepiece of a transdisciplinary practice.

Crossroads Example 3: Roundtable Sessions

Earlier this year, a group of ISF researchers, from research students to senior staff, met with the goal of strengthening and diversifying ISF's collective conception of transdisciplinary research. Our researchers' degree of engagement with theoretical and conceptual frameworks for transdisciplinary research varies from deep to none, although we would argue that all of them are frequently involved in transdisciplinary research in practice. The group organized a roundtable session and invited ISF researchers. These sessions are held weekly at ISF over lunch, usually with an hour allocated for presentation and discussion.

After drawing out individual definitions of transdisciplinary research and presenting some favourite conceptual frameworks for transdisciplinary research, the session moved into discussion. One staff member posed a wonderful question: is sailing a ship transdisciplinary? This prompted a significant pause for reflection. A response to the question took some time to emerge and our eventual response was that it is not, for two reasons. First, our definition of transdisciplinary research stresses the goal of purposive transformation in a wicked situation – in particular, a mission to create change toward sustainable futures – which is not a goal when sailing a ship. Second, we came to reflect on the political nature of the word "transdisciplinary" and the way in which it only makes sense in a context in which disciplines exist, as its starting point is a critique of those structures. It is ultimately an academic term and may be of little value to people outside academia, including sailors. This latter reflection was an important collective learning emerging from this constructed crossroads that may go on to shape the way we communicate our research approach to others.

Crossroads Example 4: Informal Unplanned Conversation

What we have learned over time is that many stakeholders expect research to be a linear, unwavering process from beginning to end, and are uncomfortable with a research project that adjusts based on new insights. That means our teams must decide whether to stay close to the expected frame or to take a systemic approach, allowing for emergence based on the complexities we collectively uncover. Both approaches are valid: the former allows more investment in data and analysis, whereas the latter requires more investment in processes with our partners about what constitutes valid and valuable research.

One of the authors was awarded national funding for a collaborative three-year transdisciplinary research project in Indonesia on how to improve the governance of community-based sanitation. Having no experience of Indonesia, she took the decision to follow an emergent approach. Costs for community-based sanitation (who paid, how much, and when) emerged as a heavily contested area. We explored people's experience of costs through two collaborative workshops in different provinces with those responsible for managing these systems, and we triangulated these against the limited literature available. This gave us sufficient confidence to stand behind a new and significant insight: that community-scale technologies placed a far higher (approximately 10x) cost burden on communities than either centralized or household-scale services.

In contrast, a colleague also working in Indonesia had identified costs as significant within a study on private water service provision, and was about to embark on a very large scale quantitative household survey to develop what she saw as a sufficiently defensible dataset. Through a corridor conversation with our colleague that began with, "How was your trip to Indonesia?", we were prompted to reflect on our research approach and to revisit assumptions of what constitutes validity in data, analysis, and claims in transdisciplinary research. We reflected that neither approach is right or wrong, but that each has different strengths and weaknesses. It was the juxtaposition of the two methods from different teams facing similar questions in related contexts that allowed us to "diffract" or see the differences that matter. As a result of this informal crossroads prompt, we revised and clarified our representation of costs to better align with the strengths of experiential insights but also the lack of statistical rigour (Mitchell et al., 2016).

Conclusion

The four examples above describe constructed and emergent crossroads where individuals come together to engage in collective learning about transdisciplinary inquiry. Others include international projects that expose researchers to different cultural perspectives on

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transdisciplinary inquiry, and guest lectures or presentations on transdisciplinary research when we check in with our colleagues on our latest thinking. In our reflection for this article, we have recognized how crucial such crossroads are for ongoing innovation in our individual and collective transdisciplinary practice. To nurture this innovation, we need to provide freedom for our researchers to exercise agency and embark on their own individual learning journeys into different contexts (topical or cultural) within shifting project teams while at the same time creating the space for emergent and constructed crossroads at which "individual learners" come back together to reflect on their learning.

There is something qualitatively different that emerges from collective reflection spaces: prompted by the clash and resonance of diverse perspectives, they are more likely to lead to "transformative learning" experiences, where perspectives shift and innovation emerges. Encouraging our researchers to travel down different paths with different people in different contexts means that the experiences and perspectives that they bring back to the collective are richer and more diverse. Consciously cultivating collective reflection spaces such as retreats, collaborative writing projects, and roundtables creates collective opportunities for innovation arising from individual learning. The individual learning journeys refresh and reinvigorate our collective learning and also have the potential to reinforce assumptions picked up along the way. We believe that transdisciplinary innovation needs both individual and collective learning: crossroads where learning journeys have the potential to intersect are essential for both. We also recognize that, while ISF strives to create such crossroads, there is much more we still need to do if a transdisciplinary practice is to thrive throughout ISF and beyond. We hope the metaphor of the crossroads will help others to structure and support innovation in transdisciplinary inquiry.

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Exploring the Transdisciplinary Learning Experiences of Innovation Professionals

Mariana Zafeirakopoulos and Mieke van der Bijl-Brouwer

> *"The personal foundation of experience of the learner comprises what learners bring to any event: their history in learning situations and more generally, their assumptions, values, conceptual frameworks, etc. They carry both the capabilities for learning further and constraints such as conceptual and emotional baggage that will make learning more difficult for them. Learners are only partially aware of their personal foundation of experience and may have great difficulty in articulating any of it."*
>
> David Boud (1993)
> Professor of Education and Professional Development

Transdisciplinary innovation inherently involves learning how to integrate disciplines towards exploring a problem or towards developing a solution or technology. Thus, transdisciplinary innovation and transdisciplinary learning are practically interchangeable. Although transdisciplinary learning has been studied and experimented with in educational research, the understanding of it in a professional context is limited. We therefore aim our research at addressing this question of how people shift their practice towards other disciplines to address complex issues. We chose to focus on a particularly challenging context – the shift from positivist to non-positivist learning across the career of transdisciplinary innovators when addressing complex problems. What makes this context challenging is that the siloed and heavily specialized nature of working within a disciplinary construct discourages collaboration on real-world complex problems. This context is also challenging because the analytic focus from positivist disciplines results in a reductionist approach, which limits an innovator's ability to explore problems holistically and abductively. An understanding of the learning experiences of practitioners in these contexts will inform the identification of relevant variables and attributes that encourage innovative learning for ultimately innovative practice. This identification might help us develop better support and education for innovation professionals who want to adopt transdisciplinary practices for the purposes of addressing complex problems. In this article, we discuss the results of a series of in-depth interviews to understand the learning experiences of design innovation practitioners who experienced a shift away from positivist approaches towards transdisciplinary innovation practice. We explore the research approach undertaken to study the motivations and drivers, the emotions experienced during the shift, and the implementation and dissemination of the new learning into professional practice.

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Introduction

With our society becoming increasingly interconnected through advances in technology and social media, the problems that our global communities face are increasingly open, complex, dynamic, and networked (Dorst, 2017). However, complex real-world problems typically do not yield to approaches that attempt to apply existing solutions. Thus, what is needed is a way to help reframe problems, and transdisciplinarity has emerged as a promising approach to meeting this need.

Since the early 1970s, when the concept of transdisciplinarity was introduced to address real-world complex problems (Piaget, 1972), several frameworks to inform transdisciplinary practice have been explored. However, this literature (e.g., Binder et al., 2015; Nicolescu, 2008; Polk, 2015) has tended towards theoretical rather than practitioner-based reflections on how transdisciplinarity is experienced by innovation professionals. There is a gap in the literature in terms of how professionals emotionally experience transdisciplinary learning to innovate for complex problem solving; for example, emotional insight reveals our likes, dislikes, underlying preferences, and values, and it ultimately determines the choices we take in what and how we learn (Moon, 2004). By exploring professionals' emotions, preferences, and values, we can better understand how transdisciplinary learning aids innovation in complex problem settings and how we might bring others – who do not apply transdisciplinary approaches – into the fold of transdisciplinary practice. Understanding the personal and emotional experiences before, during, and after learning can better inform how transdisciplinary innovation is experienced and therefore how we might embed transdisciplinary approaches in the workplace.

Complex problems require transdisciplinary approaches (as opposed to multidisciplinary and interdisciplinary approaches) such as working collaboratively across disciplines rather than "a specialisation in isolation" method (Max-Neef, 2005), adopting a systems view (Ackoff, 1999), or working continuously for a common human and social purpose (Jantsch, 1970). At the individual level, this means professionals will need to step outside their area of specialization and learn how to continuously adjust their practice with others. This type of learning goes reflecting on what we have done and how it may have contributed to an unexpected outcome (Schön, 1983). Unmet outcomes or surprising incidents occur when people offer their existing knowledge (which they know works in a specific context) to a different context where their existing knowledge is seemingly inappropriate or ill-fitting. Rather than using preconceived thinking about what should be done in a specific context, these professionals need to reflect on what works best for that unique situation, and transdisciplinarity approaches enable this reflection.

Transdisciplinarity differs from interdisciplinarity and multidisciplinary. Interdisciplinarity integrates "information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice" (Andreasen et al., 2004). Conversely, with multidisciplinarity, each discipline makes a separate contribution (Andreasen et al., 2004). By contrast, transdisciplinarity has been defined as efforts conducted by actors from different disciplines working jointly to create new conceptual, theoretical, methodical, and translational innovations that integrate and move beyond discipline-specific approaches to address a common problem (Aboelela et al., 2007).

A key feature of transdisciplinarity is the importance of continuous learning and discovery, which is especially relevant to today's workplace. Now, more than ever, professionals need to be agile in their learning and practice given they work on new challenges in new contexts, often with fewer resources, shorter timelines, and higher demand for quality outcomes. However, transdisciplinary approaches are constantly evolving (Jantsch, 1970), transcending individual disciplines and adapting to the changing reality of the complex issues that practitioners aim to address. This changing reality means that transdisciplinary practitioners will constantly need to adapt their practice, which requires them to become effective learners. In the context of innovation, the focus is currently on teaching professionals specific innovation methods and tools, such as design thinking and lean and agile methods and principles. Although these methods are useful for obvious or complicated problems, practitioners often struggle to integrate them or learn to adapt them to changing complex problems and their contexts (Snowden & Boone, 2007). We therefore argue that, to support transdisciplinary innovation, we need to better understand how we can support practitioners to become transdisciplinary *learners.* To achieve this goal, we start with building an understanding of the current learning experiences of practitioners who want to shift their practice towards transdisciplinary innovation.

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Understanding the emotional experience of learning is important because, as Boud (1993) argues, "feelings and emotions are probably much more significant influences over what and how we learn than the ostensible cognitive content". Without an understanding of experience, the successful teaching and application of transdisciplinary processes and practices may be limited to "tools" and "methods". These alone do not provide support for stepping out of comfort zones and into a dynamic learning process that underlies transdisciplinary innovation. We therefore need to include a focus on learning experiences, as Ackoff (1974) argues, to promote sustainable and systemic practice to address future complex problems. Failing to understand the emotional learning experiences of innovative approaches represents a particular challenge for structured and rules-based disciplines (e.g., engineering, medicine, or law) in which practitioners are being asked to respond innovatively to increasingly intractable problems. For these disciplines, transdisciplinary learning is less intuitive or seemingly less possible compared to non-positivist disciplines (e.g., business, design or anthropology).

As we have argued previously (van der Bijl-Brouwer, 2017), to advance transdisciplinary approaches such as those required in public and social innovation, we need to develop a more complete understanding of how and why innovation practitioners work by including the "internal view" of this practice. This is in line with the views of Wilber (2006) and Laloux (2014), who argue that effective organizational management requires an understanding of people's beliefs and mindsets, and of their collective culture. This will not just help us understand what people do in transdisciplinary innovation, but also why they do it. In seeking to define the experience of learning, we find definitions of emotion relative to learning. Emotion is defined as a multifaceted phenomenon (Scherer, 2005) and has three properties: immediate awareness, phenomenal quality, and intentionality (Reisenzein & Döring, 2009) Here, we define the experience of learning as how professionals feel during their encounter with transdisciplinary learning before, during, and after the transdisciplinary approach has been applied, and how these feelings influence transdisciplinary behaviours in practice.

In this article, we examine the learning experience provided by transdisciplinary innovation in a professional context. We explore the variables and attributes underpinning transdisciplinary experiences through the personal narratives of seven innovation professionals currently employed in areas of health, taxation, defence, bioscience, tertiary education, crime profession, and management consulting. These professionals were initially trained in rules-based disciplines such as mathematics, science, and engineering and, later in their careers, adopted transdisciplinary approaches to address complex social problems.

Methodology

The objective of this research was to identify the learning experiences of transdisciplinary innovation that could help inform how practitioners become comfortable with the uncertainty and learning required for transdisciplinary innovation and how transdisciplinary approaches are learned (beyond knowing the theoretical subject matter). The focus question guiding this research was: How do innovation professionals experience transdisciplinary learning? We theorized that this question could be examined across three phases of the learning experience to explore how innovation practitioners shifted from their original rule-based practice (positivist) to transdisciplinary ways of working (non-positivist). The three phases are explained below and illustrated in Figure 1:

1. **Pre-learning phase:** exploring the motivations and attributes of professionals that lead to transdisciplinary behaviours and ways of working

2. **During-learning phase:** exploring the process of transition between disciplines

3. **Post-learning phase:** exploring how new knowledge, practice, and ways of knowing are realized and implemented to address complex problems

To explore these focus areas, semi-structured and in-depth qualitative interviews were conducted with seven innovation professionals working in complex social problem areas across health, community justice, and public service systems. Semi-structured in-depth qualitative interviews were selected to allow subjective insights and feelings to be revealed (Neuman, 2000).

The innovation professionals were selected based on their common attribute of applying design to systemic, structural, and complex social problems and their shift away from their original "rules-based" (or positivist) discipline of study. The original disciplines of study that participants shifted away from were engineering, economics, mathematics, biosciences, science, and psychology; two participants also had additional experience in non-positivist disciplines (religion and

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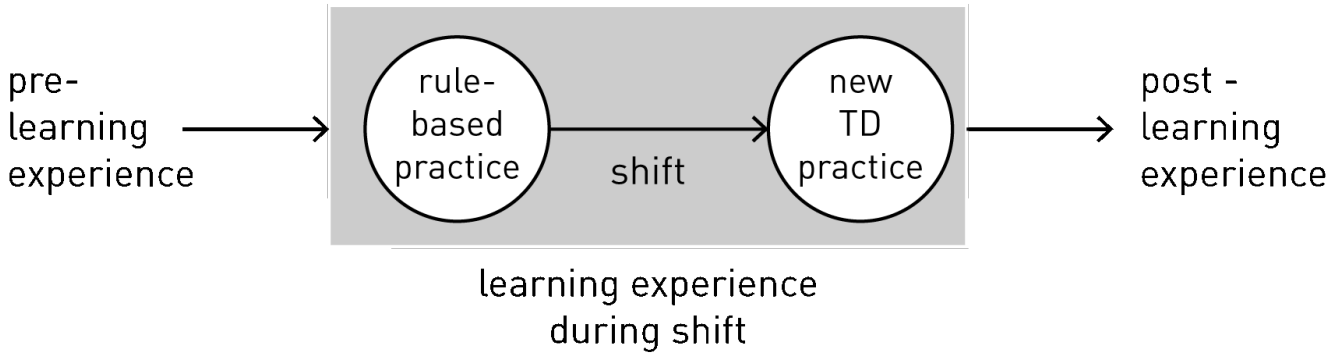

Figure 1. Conceptual research framework for examining the phases of the transdisciplinary (TD) learning experience

communications). The subjects were recruited with a snowball approach and were identified to take part in the research for their work as known senior innovation leaders currently working in innovation with a focus on addressing complex social problems such as health, population growth, crime prevention, and environmental issues.

The intent of the interviews was to unearth the feelings experienced by the professionals while undertaking their transdisciplinary innovation journey over the course of their careers. To encourage participants to discuss sentiments and reflections on their learning experience, they were asked to share their personal stories of how they came to adopt new disciplines and practices. These personal stories often included historical timelines and explanations of decisions and turning points, such as employment leaps, job changes, or moments of awareness that compelled participants to pursue one opportunity over another. These interviews were conducted over audio-visual conference calls or in person. In addition to audio recordings, hand-written notes were taken to allow the interviews to be synthesized later. In addition to taking notes about the participants' comments, observations of non-explicit communication such as tone, posture, facial expression, and vocal volume were also noted.

An inductive thematic approach was used with iterations of the analysis. First, the notes were reviewed to identify individual themes from each interview. These individual themes were then analyzed to identify commonalities or patterns across the interviews. Once this list of consolidated themes was identified, each audio file was replayed to test the themes identified – whether there were missing themes or patterns or conversely any themes that conflicted with the ruling hypothesis. The interviews were reviewed a third time for verbatim quotations as evidentiary support of the analysis.

Results

The results from the pre-learning phase highlighted the importance of emotional attitude and the influence of family in creating the appropriate environment and mindset as motivators for pursuing transdisciplinary learning. In the during-learning phase, we see participants identify the limitations of their original discipline of choice through their "doing" learning strategy and a drive to identify other approaches to bridge the gap in solving complex problems. In the post-learning phase, we identified emotional attitudes towards transdisciplinary learning as optimism, curiosity, excitement, and determination as enablers for transdisciplinary learning but also attributes that encouraged professionals to continue with their transdisciplinary approaches during challenging times.

In the pre-learning phase, there were three main motivations and attributes that led professionals to transdisciplinary behaviours and ways of working. The first attribute was the motivation for pursuing transdisciplinary learning being a curiosity in complexity, systems, and relationships. Four out of 7 participants discussed their interest in complex adaptive systems as a motivator for further problem exploration and complexity. Similarly, 6 of 7 participants interviewed discussed an interest in understanding "the system", particularly because of an interest in connections and relationships. The interest in complexity or applying a systems-view to problems affirms that it is an essential ingredient for a transdisciplinary way of working and learning, given its focus on addressing complex problems. As highlighted in McGregor (2015), "complexity is a modern

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form of universal interdependence… nothing is separate… and disparate viewpoints must be voiced and integrated to solve complex human problems."

A second attribute that led professionals to transdisciplinary behaviours was the motivation to address complex problems as influenced by family when they were young. During the interviews, it was revealed that participants had rich personal stories revealing how disciplinary and future career pathways were shaped. The example quotation below demonstrates how curiosity fuelled by family influence motivated an interest in systems. This interest eventually led to the adoption of design as a way of applying transdisciplinary ways of working to address intractable complex problems:

> *"As a child, I had long experiences of hospitalization and isolation…I got through it by patterning. I started collecting insects. I identified with systems much earlier than I knew what the word meant. I chose rural science at [university] because I was home-sick and I heard a person on the ABC who said he studied rural science because he was interested in systems, so I thought I would go and study that. I was a fiddler and inventor and dad was a good companion in that. We invented stuff out of stuff. That was how I grew up! Working with dad a lot became part of my DNA as a designer."*

In another example, a participant shares their reflections on how family played a role in their motivation to address social justice "real-world" problems – a key characteristic of transdisciplinary ways of working:

> *"My value base is very much set by my mother, my grandmother, my great-grandmother… My values come from the Welsh community, which is very much matriarchal – I spent a lot of time with my great-grandmother until she died when I was 12 and then was [best friends] with my grandmother until she died when I was in my mid-20s. My grandmother was an activist. Only in retrospect do I understand that."*

It seems, therefore, that purpose and attitude toward learning and experimentation seem to originate in people's upbringing.

An awareness of the limitation of the participant's core discipline to address complex problems' was a third attribute that bridged the pre-learning and during-learning phases. Participants identified how initial learning choices or influences were made and shifted away from those choices to find other disciplinary methods that bridged the gap. For example, participant 7 described their initial attraction to mathematics and the certainty it provided in its answers, but he then recognized as his career unfolded that, for him, mathematics had limited focus on real-world application. It was this turning point that influenced the exploration of other approaches such as design to fill this gap. This shift was common with almost all participants who looked to other fields when they realised the shortcomings of their original disciplinary pursuits. Interestingly, no participant was able to recall or describe a time when their original discipline of study was applied to design to address an identified complex problem, but 4 out of 7 participants stated that their original disciplines provided "conceptual inspiration" for transdisciplinary learning. For example, participant 3's reflections on the rules-based discipline of biomedicine helped them to become the type of design practitioner who worked on complex problems, applying methods and tools from a range of disciplines and approaches:

> *"I run experiments all the time – that's creativity... and I thought 'that's right' – I have been designing stuff ever since I left university! I now embrace the scientist in me."*

In summary, it appears that flexible, collaborative, and iterative principles as found in design can be applied to rules-based disciplines to create new ways of working, thinking, and addressing complex real-world problems. As Dorst states, design is ideally positioned to contribute as a bridge builder between technology and humanity to help deal with complex social issues (Dorst, 2017). But the reverse – the application of rules-based disciplines to design and transdisciplinary practice – does not intuitively work to address complex real-world problems. Therefore, although not all participants applied their procedural knowledge from their rules-based disciplines, the principles, familial influences, or innate characteristic that guided their original disciplinary choices provided an enduring motivation to pursue a transdisciplinary way of working.

In the during-learning phase – exploring the process of transition between disciplines – the learning strategy that participants undertook to employ transdisciplinary learning in practice was identified. Most participants reflected that their most notable experiences of transdisciplinary learning were when they were "doing" it. Five of 7 participants described their way of "learning by doing" and an additional 3 participants reflected that their approach to learning content was

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through other learning styles such as auditory or visual means, for example, undertaking prolific reading and then drawing models to interpret this reading. Although most participants described their transdisciplinary learning as learning by doing, we also witnessed that participants generated their ideas, concepts, and theories about ways to tackle complex problems in different ways, for example, reading, drawing, and sketching models or through conversations with others. It therefore appears that transdisciplinary learners (and practitioners) source their ideas in different ways but rely on learning by doing to learn from how theory is applied to complex contexts.

In the post-learning phase, we identified that learner attitude toward the learning process played an important role in adopting transdisciplinary approaches. Attitude, in this context, is defined as a settled way of thinking or feeling about their transdisciplinary learning experience. Overwhelmingly, participants described having a positive attitude towards their learning. Their positive outlook was spurred on by their desire to learn new approaches generated by feelings of excitement, anticipation, and optimism towards their learning. Participant 7, for example, described their experience as *"exciting because we were breaking new ground…doing things that others hadn't done before. Although it took several years to embody the design way…* [in other words, transdisciplinary practice], *there were clear Aha! moments."* Participant 4, for example, talked about the learning experience as exciting because *"I felt like the half of my brain which was suppressed during my structured schooling was finally freed."* Six of the 7 participants spoke of their naturally inquisitive nature and how curiosity was not only an aide to help them pursue their learning interests but also helped them to persist during times of uncertainty or difficulty. For example, participant 3 stated: *"I saw my learning journey as a continuum, I didn't know what I wanted to be in 1985 but there was always* [curiosity] *that drew me down that path."*

Participants acknowledged that, after reflecting on their learning experiences, not every experience was guided by positive emotions. Participants reported experiencing challenges when it came to external influencing factors, such as convincing colleagues of the merits of undertaking a transdisciplinary approach or pursuing organizational change in favour of more transdisciplinary innovative approaches. Five of 7 reported feeling frustrated and challenged and experiencing scepticism or self-doubt, particularly in circumstances where they needed to convince their organization or unit that transdisciplinary ways of working would be worthwhile. For example, one participant reflected on their professional experiences in facilitating a design-led workshop aimed at brokering new solutions to enduring organizational problems in the health sector. The participant reflected that few in their workshop were convinced of the merit of transdisciplinary approaches because they were wed to their world views of approaching problems in particular ways, even if these approaches failed to work. They also noted that the challenge in generating supporters and advocates of transdisciplinary approaches limits organizational transformation: *"there are always only one or two participants in a room that are converted advocates to our way of working; for most people they might find it interesting… learn a new tool or two, but they don't take it any further."* Indeed, some participants found that there were organizational barriers that represented challenges. These challenges related to how clients or partners struggle with adopting change and implementing the new tools, models, and ways of thinking they learned in the workplace, particularly if the translation to profit or improved business outcomes could not be immediately seen: *"the challenges exist when I work with clients and they experience organizational barriers...* [a focus on] *increasing revenue or market share...it is hard for them* [to implement new ways of working]."

The challenges experienced with seeking organizational change in favour of transdisciplinary and innovative ways of working had personal implications for 4 of 7 participants. These participants reported feelings of self-doubt, reduced confidence, frustration, or confusion. For example, some participants experienced frustration and confusion due to the learning curve in the new context within which they were working. Some participants were challenged to create a shift in this context by focusing on how knowledge could be applied to real-world contexts, which was different to the normative stance of their peers, which was to specialize in their respective field of knowledge. To quote one participant, they stated that they experienced challenges in *"trying to convince others of the merits of design… of making my knowledge and approach stick. I have had some great successes but also significant challenges; it has been a slow burn."* These participants persevered rather than abandoned a transdisciplinary way of working due to the advocates they found in a like-minded colleague, client, partner, or student. These individuals became advocates because they held similar attitudes – a curious mindset, an interest in exploration, and desire to realize novel outcomes for profound change. Interestingly, the same feelings of excitement, anticipation, and

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optimism that promoted their learning were also the same attitudes that helped participants through these challenging times.

Discussion

Our initial research design suggested linear shifts between the pre-learning, during-learning, and post-learning phases of transdisciplinary learning. However, the results reveal a clear feedback loop where attitudes in the pre-learning phase are enablers for a continuous learning cycle throughout the transdisciplinary practitioner's learning experience, which begins with personal histories but never actually ends (Figure 2). This feedback loop raises questions about how we amplify traditional learning approaches to better support professional learning as well as identifying the optimal tension between appropriate challenges and attitude as an enabler to constructive transdisciplinary practice.

The results of this research also generated two questions that are worthy of further exploration in the study of how transdisciplinary approaches might be shared and learned:

1. If transdisciplinary learners and innovators are driven by innate traits (for example, curiosity) shaped by early experiences and the influence of family, to what extent can these traits be taught (if at all) or reactivated in cases where innate traits in youth were trained out by specialized training in adult years?

2. If the main challenges that participants experienced are extrinsic, what are the best ways to engage with others (particularly those with different drivers) to explore transdisciplinary approaches and overcome these challenges?

The first question on teaching intrinsic drivers or traits also raises the related question: can values be taught or reactivated? Morrison (2001) posits that "we teach values by having them", whereas scholars such as Schrier and Gibson (2010) offer that values can be taught through play and gamification. It is arguable that the personal stories of youth and familial connection that participants cited were attributes, traits, and behaviours learned because of behaviour *taught* by family members. Indeed, as Adriani and Sonderegger explore in their paper on social learning, understanding parent-child relationships is an area of increasing focus for economists to explore how and which information, attitude, norms are shared across generations (Adriani & Sonderegger, 2011). If this is the case, it is questionable how formal structured learning approaches such as McCall's 70:20:10 model for learning and development – an approximate ratio that suggests for optimal learning, the majority of learning (70%) should be on the job, 20% of learning should occur through learning from others, for example, peer and mentoring support networks, and the final 10% only should be through formal learning, for example, with formal coursework – would work to create the same intrinsic drivers fused during youth (Clardy, 2018).

Transdisciplinary innovation is impossible without collaboration. This research shows that, currently, transdisciplinary innovators have very specific attitudes and motivations. Chances are that not every team member will hold those attitudes and motivations, which might impact transdisciplinary collaboration. Current transdisciplinary learners are the "early adopters" of transdisciplinary innovation, which raises the question about how these learners are going to bring others along on this journey. Indeed, the study provides anecdotal evidence that this is a key challenge for transdis-

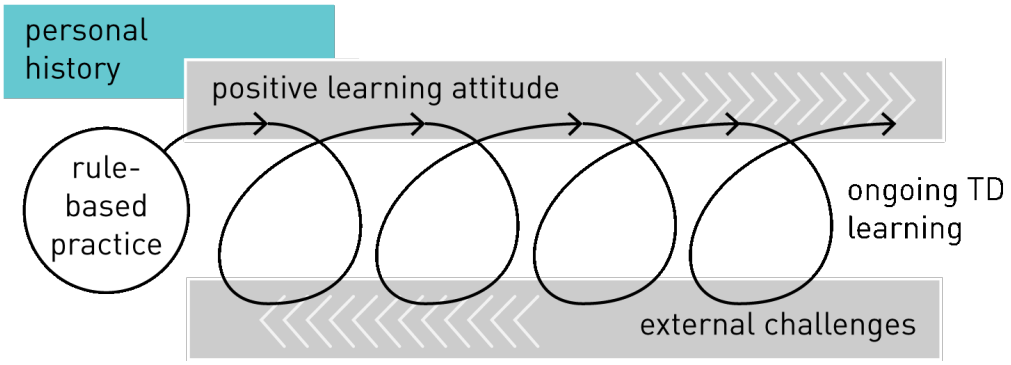

Figure 2. Enablers of the transdisciplinary learning framework

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ciplinary innovators. We therefore need to understand how transdisciplinary learning can move beyond an individual activity, to a team or group activity, building on theories such as organizational learning (Argyris & Schon, 1978), leadership theory (Dinh et al., 2014), and contemporary management theories such as Teal organizations (Laloux, 2014).

Finally, these variables verify what we intuitively assume to know about transdisciplinary innovation practices – namely, that a positive attitude toward learning is likely to yield more positive application of innovation approaches. They also verify what is known in the literature about the experience of learning more generally, which is that positive learning experiences commence with concrete experiences (Kolb, 1984). These variables also highlight a previously unidentified enabler of transdisciplinary innovation practice – the importance of familial experiences and influence in youth. These trusted family networks of support (guardian, friends, or others) are key to creating future practitioners with an innovator's mindset and a yearning interest in systems and relationships (people, process, product, etc.) and an exploratory mindset to address enduring complex problems. Familial influences embedded at youth present interesting challenges for training adults with incongruent values or adults who, as children, were subject to what Elliot Eisner refers to as the "null curriculum" – the creative learning that children "miss out on when educators lack the subject knowledge, skills, and self-confidence to deliver this learning" (Lindsay, 2015); or adults who need to be "retrained" in these variables that had them "trained out" of them during formative years.

We argue that the success of today's innovation practitioner as established transdisciplinary innovation thinkers and workers are based on their access to and involvement in supportive personal networks during their youth. But this postulation raises the question: what happens to children who have the world of possibility closed to them, whose personal networks discourage creativity, curiosity, and a drive to seek out knowledge and understanding of complex contexts? We speculate that these youth groups are less likely later in life to intuitively adopt different values, ways of working, or ways of thinking that promote innovation without external intervention, such as exposure to trusted networks that open to the possibility of working innovatively, access to an education system that further cements and celebrates the enablers of innovation, or formal training. Indeed, even formal transdisciplinary innovation training has its limitations in embedding innovation in organizational practice if it does not target the other variables highlighted in this article. There is opportunity therefore to take a collective impact approach – bringing together different organizations to achieve long-lasting social change – to the "cradle to career" student journey. The various intervention points from early education, through to secondary, tertiary, and professional education represent opportunities to spark, revive, or amplify the required attitudes that enable innovation. These intervention points can help level the playing field by providing children with equitable access to education through to adulthood that fosters and promotes curiosity, an interest in systems and relationships, and an understanding of complexity.

Conclusion

Although the search for insights into how learning is experienced is not new, this research has initiated exploration into how the experience of learning is relevant to transdisciplinary innovation. From this research, we learn that there are at least three variables of transdisciplinary learning experiences that might enable innovators to shift towards more transdisciplinary ways of working. aligned to the transdisciplinary framework of pre-learning, during-learning, and post-learning. First, participants' motivations toward transdisciplinary learning have roots in family influence, generating an interest in areas such as complexity, systems, and working on real-world problems. Second, in the during-learning phase, we see that a "learning by doing" strategy helped participants identify the limitations of their original area of disciplinary study. The consequence of these limitations resulted in participants shifting toward more generalist, holistic, and collaborative ways of working to enable a more transdisciplinary way of working. In the post-learning phase, we see that learner attitude underlies both the pre-learning and post-learning phases, playing a critical role in how professionals work in a transdisciplinary way – a learning loop rather than a linear shift from traditional discipline to transdisciplinary approaches. Moreover, the participants' emotions guided their attitude toward learning; the participants' overall learning experience was positive due to intrinsic feelings generated from making a new discovery, creating change, or pursuing curiosity. These positive emotions included optimism, curiosity, excitement, and determination. When learners faced extrinsic challenges, these positive attitudes and emotions helped them preserve with the difficulty of creating organizational change or persuading others of the merits of transdisciplinarity despite negative feelings such as self-doubt and frustration.

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These variables are ultimately important because they help us to draw from what we already know about the general emotional experience of learning as well as reflect on ways in which we can promote these variables in early childhood education through to professional adulthood. They help pinpoint enablers for transdisciplinary innovation learning and practice and help us reflect on intervention points throughout the whole-of-life education journey that practitioners undertake to spark, revive, or amplify the required attitudes that enable innovation.

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Mixing Practices to Create Transdisciplinary Innovation: A Design-Based Approach

Kees Dorst

> *We can't solve problems by using the same kind of thinking we used when we created them.*
>
> Attributed to Albert Einstein (1879–1955)
> Theoretical Physicist and Nobel Laureate (1921)

As the problems that are our organizations are facing become more complex, dynamic, and networked, they will need to become more flexible in their ability to respond. These complex networked problem situations often cannot be tackled from a single-discipline perspective, and thus transdisciplinary innovation – that is, innovation across and between disciplinary fields – is becoming more important. But how can we achieve innovation in those in-between spaces, when all of our knowledge and established approaches are held within the disciplines? In this article, we look beyond the limiting confines of traditional disciplines by seeing them as collections of smaller units of action: practices. After a foray into the anatomy of practices, we discuss how a design-based approach to transdisciplinary thinking creates a framework for the mixing of practices, articulating new insights and creating new possibilities for action in the space between the established professions.

Introduction

Over the last three decades, humanity has networked itself, to great advantage – welcome to the brave new world of the networked society – but, in doing so, we have also inadvertently networked our problems, thereby creating complex tangled webs of relationships in which progress is difficult to achieve. Our business-as-usual way to approach problems seems to be no match for the curious open, complex, dynamic, and networked nature of today's problems (Castells, 2011; Stacey et al., 2002). Our organizations and professions are struggling, and they seem to have no established way to comprehend and respond to this new type of problem situation (Boutellier, 2013). In the end, if the problems that an organization is set to deal with become more open, complex, dynamic, and networked, the organization itself will have to become more open, complex, dynamic and networked (McChrystal et al., 2015). But how can it do this?

To achieve progress in this brave new world, we have to look for new approaches and change the very way we think. Our common modes of thinking are organized in (specialized) professional fields and implemented through sophisticated organizational structures and processes. Yet, as the challenges before us become more complex and networked, innovation often seems to occur between disciplinary fields and outside of established organizations, for example, in the unstructured activities of startup ecosystems. Highly innovative people these days are often the ones who traverse disciplinary boundaries, who happen to bring deep knowledge and skills of several fields to bear on a problem or an opportunity, combining practices in a way that creates new value (Gardner, 2006).

In this article, we will explore how a design-based approach to reframing – and the understanding of practices as layered means–ends hierarchies – can help us find ways to mix practices across disciplinary fields, thereby creating the type of true transdisciplinary innovation we need to respond to today's complex, networked problems.

The Challenge: Addressing Complex Problem Situations

Before delving into the core part of this article – investigating how the manipulation of practices can lead to transdisciplinary innovation – we need to take two steps back: one to understand the context in which this

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particular type of innovation is called for and a second one to frame the process in which practices can come together in new ways.

When problems move from being very complicated to truly complex, our ways of addressing them should shift accordingly (Snowden et al., 2007). We effectively move from the field of problem solving (Simon, 1973; Hatchuel, 2001) to complexity theory and systems thinking (Ball, 2012). There, we can learn that, in very complex systems, *newness* comes from the emergence of order (rather than from goal-directed creation), *change* is achieved through influencing the system (rather than through implementing a plan to "solve the problem"), and a new *state* of relative stability can be created through creating resilience (rather than through striving for an immutable structure). These system dynamics make it hard to act upon a complex system to address issues or create newness. Any attempt at searching for "the" solution would be riddled with assumptions: in a truly complex situation, t*here is no solution.* The way to achieve progress is to create high-quality intervention to bring the whole system forward into a more desired state. (For details on how such interventions can be created, see "Transformative Theology" in Stacey and co-authors [2002]).

So, what *are* the key issues that face a professional in dealing with a complex networked situation? First of all, it is not clear where to start (this is, it is not clear how to interpret the problem situation) and, second, it is uncertain which relationships in the tangle are going to be important in shaping what would be the appropriate way forward. To overcome these challenges, we need a propositional way of working, both in the interpretation step to create an initial understanding and in the action/intervention step (to create feedback that will show which relationships in the complex problem situation are key, and which ones can safely be ignored). Although the interpretation step could possibly be covered by normal inductive reasoning, the intervention step requires design abduction, a much more open way of reasoning (Dorst, 2015). In design abduction, the practitioner enters into a thoughtful exploration by (repeatedly) proposing a framing of the problem situation, observes what possible solution directions emerge from these framings, and then reflects on the fruitfulness of their actions (is this going in the right direction?). In this way, the practitioner can navigate the complexity of the situation and "learn their way" towards a solution. In this process, assumptions, as well as established ways of working (e.g., paradigms [Kuhn, 1962]), are continually questioned.

A First Answer from Design: Framing Complex Problem Situations

Rushing into solving a problem without fully appreciating its complexity can easily lead to solving the wrong problem. And the hidden assumptions of such a rushed approach (or "knee-jerk reaction") mean that the problem solver also misses opportunities by not making a full use of the diversity of practices at their disposal. To carefully approach complex problem situations, we need to analyze them to understand how they have been framed and explore alternative framings that might lead to very different types of solutions. The ways in which expert designers create such new frames have been modelled in a frame-creation process (Dorst, 2015). Key to the creation of new frames is thinking *around* the problem situation rather than confronting it head-on. Designers have created processes that cleverly bypass the assumptions that have led to the original problem formulation and that take on the full complexity of the broader field. The creation of new frames in design can be modelled as a process of nine steps (Figure 1).

Within frame creation, new approaches to the complex problem situation are achieved through accessing practices from other fields. Central to the frame-creation process is the fifth step, where the analysis of the values of the broader field of stakeholders in the fourth step leads to a set of themes, from which new frames can be created by linking to practices from other professional fields. The first four steps lay the groundwork; the latter steps explore the implications of the potential frames and proposed solution directions (for an example, see the description of the Kings Cross project in the next section and in Dorst [2015, 2016]).

Background: An Anatomy of Practices

To understand how this frame-creation process works, we need to take one more step back and consider the anatomy of practices. A practice is a deliberate and coherent set of activities intended to achieve something. It combines a way of *seeing, thinking,* and *acting.* Models of practices (Max-Neef, 2005) generally present them as being layered (Jantsch, 1972), with the layers containing statements on the "Why", the "How", and the "What" (van der Bijl-Brouwer, 2014, 2017) (Figure 2).

The top layer describes the values you are setting out to achieve. Then there is a second layer that describes the principles and strategies chosen to achieve these values. The third layer is more tactical and describes the

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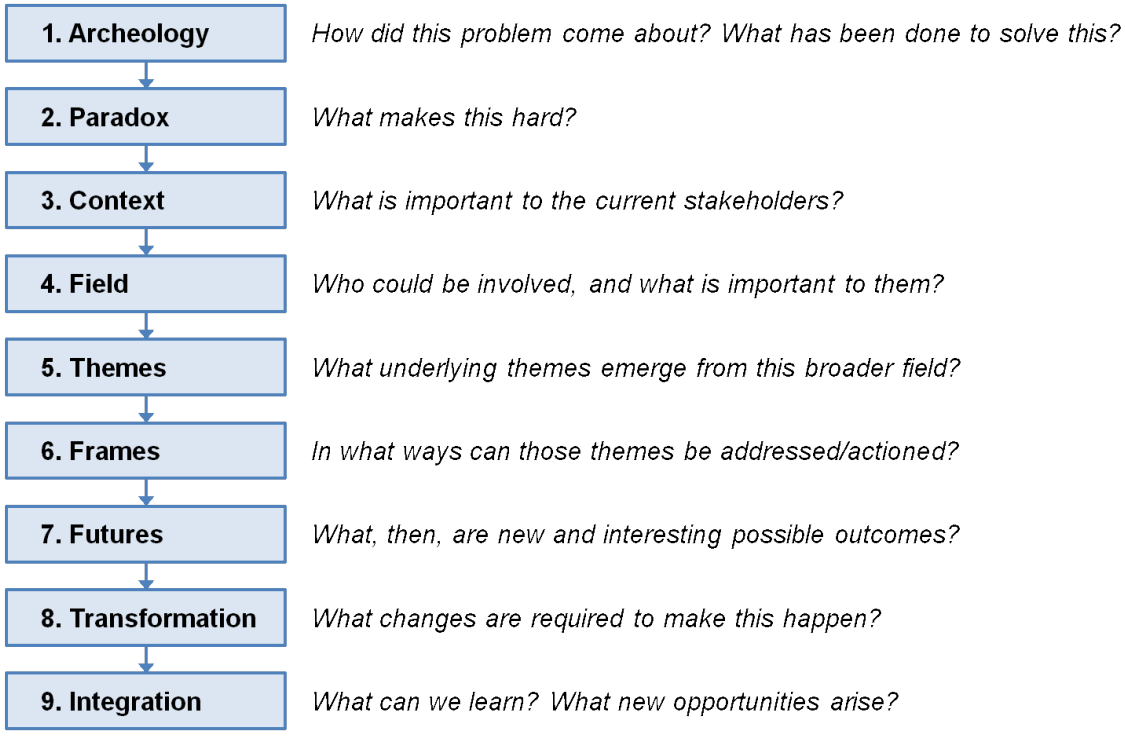

Figure 1. The frame-creation process of expert designers

"How", the method(s) through which the goal is to be achieved. The fourth layer is that of the concrete actions that are seen as part of the practice – the "What".

A framing is a statement that ties together the top two layers of the practice model: value and principle. Often, in conventional thinking, the value to be achieved and the principles through which to achieve them are merged. This merger is highly problematic because it hardwires the practice into an immutable frame. People then see one particular way of approaching the problem as the only rational one. They talk along the lines of "we have to achieve *this,* so we need to do *that*".

What makes this layered model of a practice interesting is that it opens up practices for deeper scrutiny and invites consideration of a broader range of actions, because going back to first principles (starting with values: what is this about?) makes one sensitive to the fact that any value can be achieved by multiple principles, through many different methods that lead to even more possible actions. Although a practice might look "logical" when perceived from the world of action (bottom-up in Figure 3), we can see that they are actually open-ended.

So, practices contain choices, which are often implicit choices about the values we find important, the principles we use to think about them, and the methods and actions we are going to apply. Practices also always contain a way of seeing the problem. Although that is often very implicit, the example below will illustrate how it can be hidden in the very words we use to describe a problem situation.

Frame creation is a process that expert designers developed to get around this fixation. The frame-creation

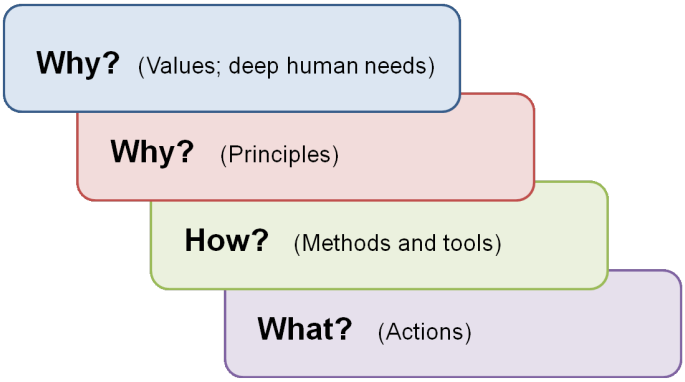

Figure 2. The four layers of a practice

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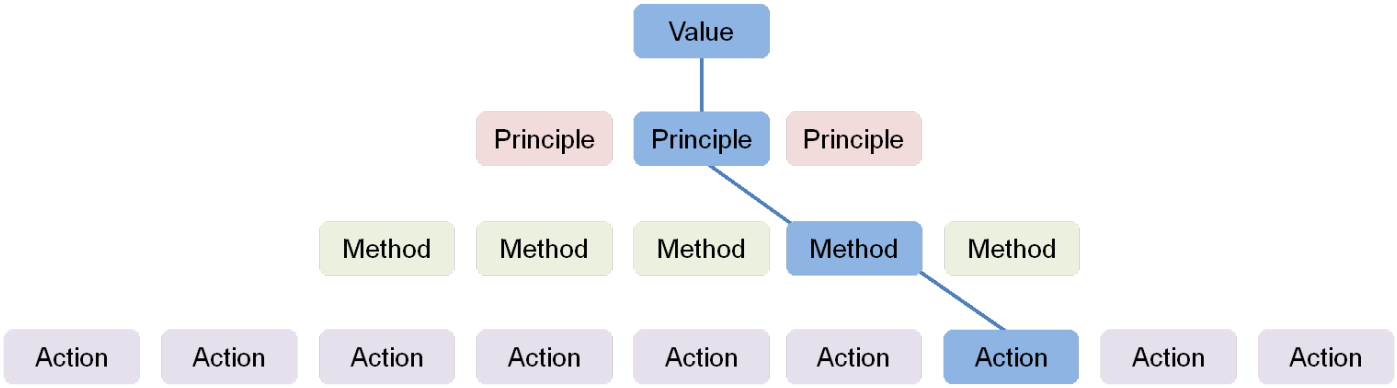

Figure 3. The open-endedness of practices

process first leads a practitioner up the four layers of practice: from considering the existing actions and methods to approaching the problem situation, back to principles and the underlying values (themes). Then, from a broad consideration of these values, new principles, methods, and actions can be proposed. This process includes a new selection of overlooked values, principles, methods, and actions that potentially could address the same problem. It also includes deriving new combinations of existing sets of them and possibly inventing entirely new methods and actions that are purpose-designed to the specific context.

An example might help to clarify how the reframing of a problem situation and the thinking of practices in terms of these four layers can be used to adopt practices that are new to the problem situation.

The late-night problems in Kings Cross, an entertainment district in the city of Sydney, have always been labelled as "alcohol-related violence". This simple statement contains the assumption (frame) that safety and security should be assured (value), by combating violence – and that the violence is causally related to alcohol consumption. The obvious way forward is then to reduce alcohol consumption because, through that step, violence will also decrease (principle). This can be done through legislation (method) and increasing the police presence to enforce the new rules (action).

This is a clear and convincing path to action, with an almost inescapable rationality, except that, in this case – upon closer scrutiny – we may see that the violence that occurs late at night is not necessarily alcohol related. A reframing of the problem is necessary, and one of the most fruitful frames in the initial Kings Cross project executed by the Designing Out Crime research centre was built on the metaphor of seeing the area as a music festival. This is a radical reframing of the problem situation, miles away from seeing it as a crime problem. Thus, the frame of a "music festival" opens up the problem situation. The new *value* set to strive for includes a vibrant, night time economy, the *principle* to achieve this by is metaphorically "creating a music festival", the *methods* to achieve this are varied, but they centre around seeing the city council as the event manager, using methods from many different professional fields (e.g., event management, behavioural psychology, economics, visual communication, education, fluid dynamics). This approach leads to fruitful new *actions:* the violence and misdemeanors could be managed by making sure there is appropriate transport out of the area late at night, providing enough public toilet facilities, diversifying the entertainment offerings, creating "chill-out" spaces, rerouting traffic, improving management of taxi queues, having "Kings Cross Guides" welcome the party goers into the area, creating safe spaces for sobering up, etc – thereby reducing frustration, boredom, and violence (Dorst, 2015, 2016).

Second Answer: Transdisciplinarity and the Mixing of Practices

Problems often arrive at an organization's doorstep as a call for action – the pressure is that we need to act, urgently, to change an unwanted situation into a better one. This means that, more often than not, the first attempts to solve a problem are based on the existing actions, methods, and principles of an organization. This makes absolute sense: the expertise and resources are available so that the problem can be solved both efficiently and at speed. Yet, knee-jerk reactions do not always suffice, and by holding on to such "best practices", we do not look beyond what worked in the past. In a rapidly changing environment, the assumptions and simplifications that were part and parcel of

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that "best practice" might not hold anymore (Boutellier, 2013). To access other practices, we need to reframe the problem situation. To break free, we need to recognize that the (routine) reactions are not the sole or necessary solution to the problem, and they perhaps offer a very sub-optimal solution. The above model of practices shows that, on reflection, there are always alternative ways of approaching a problem arena.

Yet, this is not easy. Confronted with the new complex networked reality we have created for ourselves, we struggle to step back and create new approaches: our disciplinary and organizational structures hold us back from doing so. By just looking at practices, we (temporarily) ignore these structures, routines, and norms, and we create a new playing field for fresh approaches to the problem situation to emerge. This transdisciplinary playing field comes with the freedom to branch out and learn from many disciplines that might have principles, methods, and actions that might be adopted or adapted into the problem situation.

An example of such exchanging, recombining, or mixing of practices is (a byproduct of) the development of the of a new transdisciplinary Bachelor degree at the University of Technology Sydney: the Bachelor of Creative Intelligence and Innovation (cii.uts.edu.au), which is built from the practices contained in 25 degrees across the university. During the development of this degree, a staff member from the Faculty of Design, Architecture and Building came to discuss the exchange of practices with people from the Faculty of Law. The law representatives were interested in some practices from design. They framed the question by explaining that currently, law is almost always "too late" – when a new technical development emerges, the law profession only starts focusing on its issues once the first case is brought before the court. These court cases tend to take long, be expensive, and inadvertently hold up innovation. Yet, design has sophisticated practices for "looking ahead" (scenario methods, technology roadmaps, forecasting/backcasting, etc.). Conversely, the design representative sought to learn how the law field deals with precedent – court cases are kept and archived as situated knowledge so that, when the need arises, the earlier judgment can be retrieved and the old context in which it arose can be compared with the current one before the court. A subtle language game has been built up to guide the interpretation. This practice is in marked contrast to the field of design, which has no systematic way of dealing with memory at all: when designing for a current challenge, one might be trying to use an earlier design instance for inspiration, but there is no way for the designer to identify the most appropriate earlier design and access the contextual information needed to understand it. Thus, the field of design has a lot to learn from law – not by adopting the practices as they are, but by adapting them to fit the field (Dorst, 2017).

Conclusion: Towards Transdisciplinary Innovation

As we have seen, the frame-creation process provides us with a thoughtful way to re-interpret and rethink existing problem situations, and to identify practices from various fields and disciplines that could be brought to bear (as shown in the first example above). We reframe when we are forced away from our normal (knee-jerk) action orientation and have to go back to first principles. From this deep rethinking, we can then access the broadest possible collection of principles, methods, and actions, while considering how they may assist us. This type of deeply considered innovation-between-fields leads to the adoption of principles and practices that are completely new to the problem situation.

While framing "reshuffles" the position of practices relative to complex issues, the description of practices in terms of the four layers also opens up the possibility and the freedom for practices from different fields/backgrounds to be mixed and cross-linked in an open "practice dialogue" (such as happened in the second example above).

Reframing and the capability to create open practice dialogues are key elements of the transdisciplinary thinking we need to deal with today's open, complex, dynamic, and networked problem situations. In leaving behind the stable structures of disciplines and organizations, one learns to truly value the practices they contain.

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Start by asking yourself:

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