Leveraging Transdisciplinary Engineering in a Changing and Connected World
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The Pathway to Sustainability in Transdisciplinary System Development

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Abstract. In support of a conference theme 'leveraging transdisciplinary engineering in a changing and connected world, this paper examines potential pathways to sustainable development in one system of systems supporting the implementation of United Nations Sustainable Development Goal 6: 'Ensure availability and sustainable management of water and sewage for all'. We investigate a 20-year journey of an innovative Australian water utility committed to customer and community engagement that also has to embrace an increasingly wide range of technologies to achieve this. The practices established evolved from learning via a myriad of projects and more recent ones employing digital technologies may be viewed collectively as an instance of 'Water 4.0'. Some projects drew on disciplines founded in the social sciences, some on physical science, computer science and engineering disciplines, and some on a combination. The sustainability pathway evolved in response to external drivers via unique sets of pilot projects followed by further development and deployment. Suggestions for further research are provided.

Keywords. Industry 4.0, Sustainability, Transdisciplinary Systems, System of Systems, X4.0

Introduction

Research into multi-disciplinary systems and system lifecycle assessment have raised new concerns on how sustainability can be assured while changes in technologies and actors in the systems are consistently entrenched into the traditional development pathway of such systems [1]. The evolution of transdisciplinary systems has been influenced by both the nature of the adopting industry and 'Industry 4.0' developments. It is clear that transformation within a transdisciplinary system is a gradual evolutionary process which involves stakeholders in creating and maintaining quality services and exchange provision of services. This paper has been written to explore the conference theme "Leveraging Transdisciplinary Engineering in a Changing and Connected World." It is observed that today's complex problems, especially those that have a large impact on the environment and society, require a holistic approach to solving them by considering knowledge from a diverse range of disciplines, technical as well as social, and from user and practitioner communities. The complex problem of 'Ensuring availability and sustainable management of water and sanitation for all' framed in the United Nations Sustainable Development Goal (SDG) 6 https://unric.org/en/sdg-6/ has

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demanded stringent industry practice in compliance. Brennan et al [2] suggested "*a transdisciplinary approach is one way of better understanding potentially conflicting viewpoints evident in discipline-based approaches to sustainable development, global water challenges and water security.*" Some industry-specific technologies are evolving and some may be applied across industry sector boundaries. A European industry study [3] introduced the term 'Water 4.0' to describe the interactions between innovative current and future networked technologies with water as the product focus. In TE2019, this concept had been demonstrated from a high-level system of systems development viewpoint, indicating that transdisciplinary engineering can help create a model of evolutionary X4.0 [4]. This paper exploits the underlying concept and capability development practice further using a study of recent sustainability efforts in the water industry. Many prior transdisciplinary engineering studies have examined engagement with academia. The research question being explored here is: *how does transdisciplinary engineering practice evolve in an industry practitioner sustainability setting?* A brief review of literature framing project context is supplemented by a single explanatory longitudinal case study of an Australian enterprise responsible for both clean water distribution and sewage management. A previously published 3PE transdisciplinary system model [5] is utilised to consider both developmental activities and the operation of the evolving product-service system.

1. Transdisciplinary Engineering and Some Matters of Context

Our on-going interest is on interaction for mutual benefit in the evolution of systems of systems in complex operating environments where a particular socio-technical system may be viewed as an element of a larger socio-technical system [6]. Wognum et al [7] observed "Many engineering problems can be characterised as ill-defined and socially relevant, too. Although transdisciplinary engineering cannot widely be found in the literature yet, a transdisciplinary approach is deemed relevant for many engineering problems." In the following we consider three matters of context: (a) ways of characterising transdisciplinary engineering, (b) socio-technical system scenarios and (c) complex operating environments. We then identify a major knowledge gap to be explored in this paper.

1.1. Characterising Transdisciplinary Engineering Practice

Krueger et al [8] argued for more agonistic water research relationships: in addition to adopting transdisciplinary and participatory approach with relevant technical knowledge, projects should try to integrate social context and political engagement. Brennan et al [2] suggested a three-element model comprising: (a) a problem representation activity to identify compatible goals, (b) a language organisation activity to support working across boundaries, and (c) contextual setting considerations. Lattanzio et al [9] explored perceptions of transdisciplinary engineering practice by engaging with 34 participants at an international conference on the subject. Despite different nuances, a common theme was problem-focused academic and non-academic participants working with a high level of integration. They noted a variety of viewpoints and represented the outcome as framing a 'transdisciplinary landscape' having three inter-dependent characteristics: (a) the **goal** (e.g., research, development or deployment focused on real-world, socially relevant problems; (b) **collaboration** (e.g., local / global, societal, professional), and (c)

integration (e.g., users, technologies, dissolution of boundaries, adapted methodologies reflecting context).

1.2. The Notion of Socio-Technical Systems and Associated Competencies

Davis et al [10] promoted the idea of extending the application of socio-technical systems thinking beyond the historic application to technology and work design to expand notions of what constitutes a system and to apply such thinking to a much wider range of complex problems and global challenges. Our representation of four generic application scenarios with transdisciplinary engineering examples is shown in Table 1.

Table 1. Social and Technical System interaction scenarios

System Enabler	System Application	
	1. Social	**2. Technology**
A. Social	Facilitating interaction between and within social and professional actor groups for mutual benefit, e.g., in transdisciplinary engineering education	Social agents developing, deploying and adapting technology applications, e.g., in transdisciplinary engineering technology diffusion projects
B. Technology	Technology supporting the achievement of societal goals, e.g. in transdisciplinary engineering contributions to UN sustainable Development Goals realisation	Technology platforms supporting independent / interdependent technology actors, e.g., in transdisciplinary projects associated with the world of X4.0

While researching management issues in the agricultural water sector, Mollinga [11] identified three competencies that a transdisciplinary system engineer should have: (1)) internalising ecological concerns, (2) co-evolution of water system in technical, infrastructural and social aspects, (3) constructive involvement of interest groups in the systems engineering lifecycle. In this notion, any socio-technical interaction scenario could be conveniently represented by a system model known as 3PE incorporating multiple perspectives: people, product and process interacting within an environment [5].

1.3. Complex Operating Environment Characterisation

The complex operating environment associated with transdisciplinary practice has been characterised in a number of ways. Sage and Cuppan [12] adopted a systems perspective and observed that "*systems that are themselves comprised of other component systems, where each of the component systems serves organizational and human purposes. These component purposes may be locally managed and optimized independently, or nearly so, for the objectives to be met by the composite system*" They argued that such systems generally possess the characteristics of complex adaptive systems. Rogers et al [13] investigated the diffusion of innovation as a complex adaptive process where human actors or nonhuman actors (e.g. machines, computers) and external factors (e.g. acts of nature) interact to adopt and adapt particular practices. Preiser et al [14] have suggested that socio-ecological systems (such as those associated with water management considered in this paper) are themselves examples of complex adaptive systems. From a different perspective, Phillips and Ritala [15] noted that an ecosystems analogy has emerged as a field of study in organization and management research and that viewing such ecosystem as a complex adaptive system could have some advantages in (a) defining boundaries and different perspectives, (b) in understanding hierarchies and relationships, and (c) in observing the dynamic and co-evolution aspects of such systems. Laszlo and Krippner [16] noted that complex systems theory had originally evolved as a transdisciplinary collection of concepts from physics and economics to sociology and ecology. The point here is that transdisciplinary action is needed at multiple levels in coping with complex operating environments.

1.4. Knowledge Gap

What we take from the above is that adopting a systems-of-systems perspective in a transdisciplinary engineering study must include consideration of boundaries, actor relationships and changes over time. As the world is moving to an Industry 4.0 backbone, how industry takes advantage of transdisciplinary approach and socio-technical influence is yet to be explored.

2. The Research Approach

Our research question was: *how does transdisciplinary engineering practice evolve in an industry practitioner sustainability setting?* An exploratory longitudinal case study has been utilised. According to Yin [17] this is appropriate when investigating 'how' questions in a contemporary setting. We have selected an Australian, government-owned, for-profit, water utility, Yarra Valley Water (YVW) as our study case enterprise [18]. The selection criteria used were:

- Established, stable operation
- Evidence of innovation on multiple fronts and an established market for recycled resources
- Ready access to data from multiple sources (120+ company, supplier and government news releases, 11 years of annual reports, and more than 50 engineering and business academic publications from 2000 - 2022 related to YVW)

Yarra Valley Water (YVW) was established under the provisions of the Victorian State Water Industry Act 1994 and began operation on 1 January 1995. From 1 July 2012, became a corporation subject to regulation by the Essential Services Commission, making payments to the Victorian Government equivalent to the income tax and sales tax that would be payable if it was not a statutory corporation. The Corporation is responsible for the control of water supply headworks, major wastewater treatment, and transfer infrastructure and drainage in its region which covers the Yarra River catchment area to the east and north of metropolitan Melbourne, an area covering over 4,000 square kilometres. Its work covers 15 local government municipal areas responsible for more than 10,000kms of water mains and approximately 10,000kms of sewer mains. YVW provides drinking water, sewerage, recycled water and trade waste services to more than 1.9 million residents – almost 30 per cent of Victoria's population – and over 60,000 businesses across Melbourne's northern and eastern suburbs. It has a revenue of about A$1B pa, manages more than A$5B in assets and directly employs about 600 people. It has won numerous national and international innovation awards in the last decade.

3. Analysis of the Case

Data obtained from multiple YVW sources was organised into eleven 12-month sets of transformational annual events from 2011 plus one pre-2011 set to identify trends and the nature of changes taking place. Each set was then examined to identify transdisciplinary project activities. The YVW pathway to sustainability has not only involved meeting SDG6 targets for water and sanitation services, but also elements of SDG7 (affordable, clean energy), SDG11 (sustainable cities and communities) and SDG12 (responsible consumption and production). All require community engagement and interaction with an increasingly diverse range of professional disciplines, including those associated with the use of Industry 4.0 technologies. An emergent YVW system of systems network of functional activities is illustrated in figure 1.

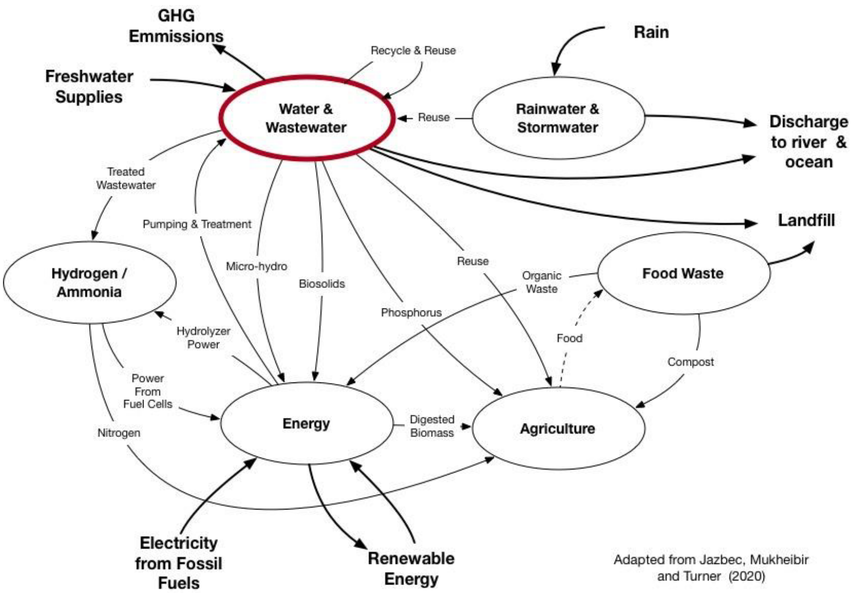

Figure 1. YVW Systems of Systems Model (adapted from [19]).

Five primary external change episodes stimulating several projects over a 20+-year period were observed (see Table 2) and the 3PE model was used to provide a conceptual framework for semantic and logical analysis. The following analysis is segmented according to the 3P's and environment structure.

3.1. Environment: Drivers of Change

Due to government policy changes, YVW had to progressively update its' activities over the years. The early establishment of an innovation culture within YVW supported meeting these commitments (e.g. Crittendon et al [20]). Climate driven events, technological developments and commitments to UN Strategic Development Goals have stimulated change in YVW via a myriad of exploratory pilot projects followed by infrastructure development. An overview of five major drivers of change and their impact is shown in Table 2.

Table 2. Drivers of change impaction Yarra Valley Water (YVW).

Driver of Change	Impact and Indicative Response
Ongoing: Population Growth – Greater Melbourne area population growth 50% every 30 years	Ongoing need for water and sewage network expansion, opportunities to incorporate new technologies along the way. Two new districts established as 'innovation hubs' hosting recycling and new technology initiatives (e,g., over 700 km of recycled water mains installed)
The 2000s: **Millennium Drought** – 1999 requirement for improved quality of wastewater released; 2004 long term plan with 110 water conservation initiatives	YVW participated in many project initiatives, including a smart water fund program that supported 280 community, business and academic water conservation project over a 15-year period. Integration with large-scale supply initiatives – an expanded state-wide supply grid including a de-salination plant
From 2005: **Water Treatment Technology Developments** – multi-stage closed sewage biodigesters replacing open ones, electricity generation from biogas, new technology filtration	Land previously allocated for agriculture using processed effluent for irrigation now available for residential / commercial use incorporating smart water system technologies, recycled water, better managed stormwater flows. More efficient, reduced cost processing plants. Electricity generation from waste food and sewage processing biogas.
From2012 : **Industry 4.0** - progressive integration of digital office and delivery automation, data analytics and cyber-security technologies	Increased on-line customer engagement, district-level and householder smart water metering to map water usage patterns and help develop leaks early with the help of artificial intelligence tools, Development of a water network 'digital twin' to help model supply growth patterns and forecast annual need in conjunction with meteorology practitioners
From 2016: **UN SDGs – flow-down of obligation** to support Victorian State Government commitment to target. YVW to achieve net zero energy usage by 2025	On-target to achieve net zero carbon by 2025. Renewable energy generation from established assets. Hydrogen generation planned using clean treated effluent and excess electricity from in-house facilities. Contribution to circular economy converting food waste to electricity and fertiliser products

3.2. People: Societal and Multidisciplinary Engagement

Actor-network theory utilised in the social sciences views both human and non-human agents as actors [20]. Transdisciplinary engineering collaboration continues to evolve through actors engaging with emerging technologies as indicated in Table 2, via personnel secondment with other Victorian Government departments and via mentoring water utilities in developing economies. The innovation culture underpinning both YVW societal and technological engagement has been shared with and adopted by the American Waste-Water Institute [21] has a three-component structure: (1) focus on and provide feedback on impact projects; (2) maintain evaluation and development capability; and (3) pursue multi-faceted engagement including consideration of reach.

Water industry requirements change over time. YVW has been driven by changes in the environment including mandates set by the government on continuous improvement. For example, due to population growth, YVW promoted use of rainwater and stormwater as supplement to water supplies. Later, YVW was driven by drought to coordinate actively with the agriculture sector. Developments in water treatment technologies and the emergence of Industry 4.0 technologies pushed the boundary further to where renewable energy integration is a fundamental expectation. How sufficient renewable energy could be generated had substantial implications. Demonstrating compliance with international requirements outlined UN SDGs added further challenges. Furthermore, YVW established a 'citizen jury' to help judge what is important to its' clients in future planning. In engineering projects YVW assembled teams that may include water engineers, digital process control engineers, biological process experts, renewable energy experts, and data modelling /analytics experts. Some employees had job titles like 'hydraulic modeller' reflecting the transdisciplinary nature of their work.

3.3. Products: Moving from a Linear Flow Regime to a Circular Flow Regime

YVW has moved from a linear water usage model (extract, use, dispose) to a circular economy one [18], giving it additional products to sell: recycled water from multiple sources, fertiliser products, excess electricity, and in the near future, green hydrogen. It has developed and patented its own consumer digital water meter, which involved multiple interactions between the community and a range of engineering disciplines in it development and deployment. YVW also offers additional services: providing efficient micro processing systems to off the (sewage) grid customers and promptly advising of potential customer property water leaks through its smart meter systems.

3.4. Processes: Production Processes and Water 4.0

The German Water Partnership [3] has declared "*WATER 4.0 focusses on digitalisation and automation as the core aspects of a strategy for resource-efficient, flexible and competitive water management.*" YVW has been implementing digital process control systems in its established and new pumping and processing plants since the late 2000s. It has been installing digital flow meters both at district grid locations to detect leaks or blockages in its own pipelines and at customer premises. In 2016 YVW mapped out an intelligent network strategy. It subsequently developed a 'digital twin' of its water flow network in conjunction with an Israeli-based company that has incorporated artificial intelligence tools in the model. The model is progressively updated and used for system modelling. Digital technology is also being enhanced in business processes and is being ported to cloud-based IT resources, with a customer interface for reporting and tracking problems. As illustrated in figure 1, the variety of processes to be managed has increased beyond just the provision of water and sanitation services and each one of these processes requires engagement with societal actors at multiple levels.

4. Sustainability and Transdisciplinary Engineering Evolutionary Pathways

In the YVW case a combination of an internal culture supporting innovation and change with external developments (e.g. the millennium drought, industry 4.0 developments, commitments to UN SDGs) has stimulated the evolution of transdisciplinary engineering practice via a myriad of projects. These projects cover the range of socio-technical scenarios outlined in table 1. Establishing a baseline position through pilot projects was the norm, followed by another round of development to either increase scale or increase the scope of YVW operations. We suggest this is consistent with the advice of Waddock et al [1] on how to work with 'wicked problems': (a) recognise the central role of culture; (b) distinguish between incremental, reform, and transformational change; (c) prioritize learning in the context of constant change, (d) work with a co-evolution and emergence action framework, and (e) emphasize resilience and adaptation. Viewing the YVW case from this perspective could be a topic for further research.

4.1. Transdisciplinary Development

Mo and Beckett [4] noted that transdisciplinary **systems development** involved working across multiple boundaries. They presented a generic Industry 4.0 model that could inform two iterative stages of transdisciplinary system deployment based on the work of Wognum et al [22]. The development stage assembles a coalition of different disciplines, social as well as technical, that are needed to fully exploit the effects, implications, advantages, socio-technical adaption issues. The outcome is a product service system (PSS) that satisfies customer requirements, and its deployment and ongoing support may require transdisciplinary action. In an Industry 4.0 context, within each stage, there may be interactions between an automation engineering domain (e.g. YVW plant automation and smart sensor deployment), a data analytics domain (e.g. YVW digital twin development), a data integrity management domain (e.g. YVW initiatives to protect client personal data) and an associated knowledge / skills domain (e.g. YVW establishment of cross-disciplinary roles like hydraulics modeller). Working with data is at the core of Industry 4.0 initiatives that influence all parts of enterprise operations. At the same time stakeholder knowledge provided to and provided by transdisciplinary engineering projects supports the confrontation of potentially 'wicked' societal problems. Consistent with the observations of others [8] transdisciplinary engineering may not be a term regularly used at YVW. We suggest transdisciplinary **capability development** is ultimately embedded in the organisation culture and reinforced in tackling projects that have a significant societal impact. Table 3 shows a comparison of elements of YVW embedded culture with some transdisciplinary engineering attributes described in the literature. Expansion on this aspect may be a topic for further research.

Table 3. A comparison of YVW practice with transdisciplinary engineering (TE) Characterisations.

YVW Embedded Culture	TE Project Characterisation	TE Water Challenges
Focus on **impact** in choosing projects, adapt to optimise outcome delivery, and further evolve practices once a platform is established	**Ill-defined and socially relevant problems** [7]. An explicit intent of solving a real-world problem [9]	**Problem representation**: engagement with a societal problem requiring an integrated approach beyond just filling gaps in discipline knowledge [2]
Maintain and access in-house and key partner **capabilities** to evaluate and develop projects.	**Integration** - a shared problem formation and common methodological framework --- three key themes: systems perspective; weighting of disciplines; transcending of disciplines and disciplinary knowledge [9]	**Working across boundaries**: water knowledge extends beyond that of scientists and other certified experts. *Even disciplines that are philosophically cognate have methodological differences that may hinder interdisciplinary research* [8]. Finding a common language [2]
Engagement - targeted engagement with key stakeholders, broad reach, regular communication	**Collaboration**: the need for collaboration between academics and non-academics -- and to a lesser extent for inclusion of social science disciplines - -- to acquire the necessary knowledge about users and context [9]	**Contextual setting**: the significance of time and place, understanding different perceptions of value [2]. Water management has a political dimension requiring engagement with civil society and the private and public sectors [8]

4.2. The emergence of a global water engineering business ecosystem

Much of the transdisciplinary engineering literature provides an academic perspective, considering *problem-focused academic and not academic participants working with a high level of integration* [9]. But our case observations suggest there is a parallel body of work adopting a practitioner perspective. We observed Industry Associations (e.g., the Australian Water Association, German Water Partnership and American Waste-Water Association) acting as intermediaries in exploring multiple technology themes in parallel via special interest groups. These groups and their members undertook some joint international projects together and were sharing their experience with water utilities in developing economies. The evolution of this 'ecosystem' could also be a topic for further research.

5. Concluding Remarks

Our research question was: *how does transdisciplinary engineering practice evolve in an industry practitioner sustainability setting?* An exploratory longitudinal case study - Yarra Valley Water (YVW) was utilised. YVW manages three kinds of projects that may involve transdisciplinary engineering practice: (a) infrastructure extension projects in conjunction other stakeholders, (b) new / adapted technology projects to enhance system capability, and (c) problem-solving operational projects to enhance system performance. Operational detail was explored using a 3PE model [5]. An internal innovation culture and emergent 'wicked problems' have resulted in the implementation of an expanded portfolio of capabilities that yielded additional products, each involving engagement with additional disciplines, and all involving interaction with community stakeholders. A still-evolving digital technology overlay on all parts of the business has been referred to in the YVW industry as 'Water 4.0'. There are interactions between people, products, processes and the operating environment. Evidence from these studies shows that there are evolutionary pathways for migrating multi-disciplinary projects into transdisciplinary projects, which ultimately should contribute towards achieving sustainability. In the YVW case this pathway may be viewed as a helical rather than a linear process, first establishing capability and building credibility through pilot projects, then increasing scale and or scope building on the previously established platform. In navigating through their pathway, partners see value in exchanging services and knowledge. Many formal and informal engagements (hence interactions) are established in addition to contractual obligations. Suggestions for further research are: (a) explore the approach to 'wicked problem' management suggested by Waddock et al [1] that would also consider the development of a transdisciplinary engineering culture, and (b) characterise the evolving water industry global knowledge ecosystem.

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