Harvey Fox

An Integrated Knowledge Transfer Framework for Enhancing International University-Industry Collaboration in Novel Sanitation Technology Development

Centre for Design Engineering
PhD in Design

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Academic Year: 2020 - 2023

Supervisor: Dr Adriana Encinas-Oropesa
Associate Supervisor: Paul Lighterness
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Abstract

Approximately 3.5 billion people worldwide lack access to safe sanitation services, a challenge that demands innovative solutions. University-industry collaborations (UICs) are increasingly recognised as a means to develop and commercialise cutting-edge technologies addressing such global issues. However, these partnerships face complexities in transitioning lab-based inventions to market-ready products, especially during the critical stages of technology development and refinement.

This thesis presents an integrated knowledge transfer framework for international UICs, focusing on the development and commercial handover of novel sanitation technology. Through a series of interconnected studies, the research explores the micro-level interactions and processes within the execution phase of international UICs. The framework synthesises insights from three key studies: field testing dynamics in cross-cultural settings, which reveals the effectiveness of diverse team structures in different geographical contexts; a novel iterative development process (ERDE: Experimenting, Reviewing, Distributing, Executing), which provides a structured approach to capturing and integrating multi-modal feedback from dispersed partners; and the role of physical and digital boundary objects in technology and knowledge synchronisation across dispersed partners, highlighting the challenges and successes of alignment between university and industry collaborators. Each study contributes unique insights: the field testing research informs practices for geographically dispersed collaborations; the ERDE framework addresses challenges in the technology 'Valley of Death' by facilitating decentralised development; and the boundary object study emphasises the need for adaptive communication strategies across cultural and institutional boundaries. By examining a range of critical activities in technology development, this research contributes to both theoretical understanding and practical management of knowledge transfer in international UICs. The integrated frameworks offers a comprehensive approach to navigating the complexities of geographically dispersed innovation processes and facilitating knowledge alignment within international collaborations, particularly for

technologies intended for diverse global contexts. This work has implications for academics, practitioners, and policymakers involved in developing and transferring innovative technologies across institutional and international boundaries to achieve far-reaching societal impact.

Keywords: Technology development; Technology transfer; Valley of Death; Innovation; Sanitation

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There are a few thoughts I want to reflect on towards the end of this journey.

I'd like to thank the research sponsor, the Bill & Melinda Gates Foundation, for initiating this aspirational project (the Reinvent the Toilet Challenge) that I am humbled to have been able to contribute towards in my own small way. Working with partners from all across the globe, albeit mostly virtually, has expanded my capacity to think past my immediate surroundings and understand that for large societal challenges to be solved that several countries and institutions must come together. Despite inherent challenges, common in such ambitious landscapes, it has been an in-valuable experience to be a part of. One day, in the near future, this challenge will have been solved. How incredible to think about.

I came into the Centre for Design Engineering (C4DE) from a different disciplinary background but was welcomed into their open and multi-disciplinary arms. Throughout this time period, I have had the opportunity to grow immensely as an individual and be exposed to many talented individuals from which I have learned a great deal from.

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Figure 0. Harvey Fox (Author) Involved in Various Project Activities (2023)

Table of Contents

Abstract i
Acknowledgements iii
List of Figures ix
List of Tables x
List of Abbreviations xi
1 Chapter 1: Introduction 1
1.1 Research Background 1
1.1.1 Research Environment 4
1.2 Aim and Objectives 7
1.3 Research Methodology 8
1.4 Contributions of the Thesis 11
1.5 Thesis Structure 13
1.5.1 Papers Written as Part of Thesis 14
References 15
2 Chapter 2: From the Lab to Another Country's Field: Investigating Team Dynamics and Operational Insights in International Field Testing Campaigns 21
Abstract 21
2.1 Introduction 22
2.2 Context and Methodology 23
2.2.1 Project Context 24
2.2.2 Data Collection 27
2.3 Empirical Findings 32
2.3.1 Team Size and Structure 32
2.3.2 Division of Labour Across Activities 33
2.3.3 Time Taken to Complete the Campaign 36
2.3.4 Qualitative Findings 37
2.4 Discussion 40
2.4.1 Summary of Quantitative Findings 40
2.4.2 Summary of Qualitative Findings 40
2.4.3 Managerial Implications 41
2.4.4 Limitations and Future Research 43
2.5 Conclusion 44
References 45
3 Chapter 3: Crossing the Valley: Enhancing Technology Maturity in International University-Industry Collaborations 47
Abstract 47
3.1 Introduction 48
3.2 Theoretical Background 50
3.2.1 University-Industry Collaboration and Technology Development 50

3.2.2 The Valley of Death 52
3.3 Context and Methodology 57
3.3.1 Cranfield Circular Toilet Project 58
3.3.2 Activate Partners in the Project During Investigation 59
3.3.3 CCT Stage of Development 60
3.4 Introduction to the ERDE Process Framework 61
3.4.1 Experimenting Stage 65
3.4.2 Reviewing Stage 65
3.4.3 Distributing Stage 66
3.4.4 Executing Stage 66
3.5 Implementation of the ERDE into the CCT Project 67
3.5.1 Improvement Log and Tracker 67
3.5.2 Improvement Observation Card 73
3.5.3 Presentation Metadata Card 75
3.5.4 Linking the Artefacts and the ERDE Together 79
3.6 Discussion 80
3.6.1 Theoretical Contributions 80
3.6.2 Managerial Implications 82
3.6.3 Limitations and Future Research 83
3.7 Conclusion 83
References 84
4 Chapter 4: Gather Around Your Toilet: Synchronisation in an International University-Industry Collaboration 94
Abstract 94
4.1 Introduction 95
4.2 Context and Methodology 98
4.2.1 Reinvent the Toilet Challenge – Rethinking Sanitation 99
4.2.2 Cranfield Circular Toilet – Case Study Context 99
4.2.3 Overview of the Synchronisation Process 100
4.2.4 Synchronisation Protocols 104
4.3 Empirical Findings 109
4.3.1 Commissioning Results 109
4.3.2 Clean Water Experiment Results 109
4.3.3 Conveyance of Toilet Paper Experimental Results 112
4.4 Discussion 114
4.4.1 Summary of Empirical Findings 115
4.4.2 Theoretical Implications 117
4.4.3 Managerial Implications 118
4.4.4 Limitations and Future Research 119
4.5 Conclusion 120
References 121
5 Chapter 5: Discussion – An Integrated Knowledge Transfer Framework 126

5.1 Introduction to Framework 126
5.2 Chapter 2's Positioning and Contribution 129
5.3 Chapter 3's Positioning and Contribution 130
5.4 Chapter 4's Positioning and Contribution 134
5.5 Key Considerations and Recommendations 139
5.5.1 Field Testing 139
5.5.2 ERDE Process Framework 140
5.5.3 Synchronisation Process 141
References 143
6 Conclusions 146
6.1 Summary of Aim Achievement 146
6.2 Contributions to Knowledge 148
6.2.1 Team Dynamics and Operational Considerations for International Field Testing 148
6.2.2 Experimenting, Reviewing, Distributing, Executing (ERDE) Process Framework 148
6.2.3 Synchronisation Process for Technology Handover 149
6.2.4 Integrated Knowledge Transfer Framework 150
6.3 Limitations and Future Research 153
Appendices 155
Appendix A – Data Management 156
Appendix B – Photos of Project Activities 157
Appendix C – Examples of Synchronisation Protocol 159
Appendix D – Example of Instruction Manual 169

List of Figures

Figure 1-1 Adapted double diamond research methodology 10
Figure 1-2 Illustration of the thesis structure 14
Figure 2-1 Basic diagram of subsystems 25
Figure 2-2 Project partners and those involved in field testing campaign 25
Figure 2-3 Data structure formed from field testing feedback 31
Figure 2-4 Organogram of the Indian field testing team 32
Figure 2-5 Organogram of the South African field testing team 33
Figure 2-6 Gantt chart timelines of field testing campaigns 37
Figure 3-1 Cranfield Circular Toilet prototypes 58
Figure 3-2 ERDE process framework 62
Figure 3-3 Visual model of the SURT system and traffic light capability scale . 68
Figure 3-4 Example of the IOC in use 73
Figure 3-5 Example of the PMC in use 75
Figure 3-6 Example of the PMC used at interval progress updates 77
Figure 3-7 Interlinked artefacts facilitating the ERDE stages within the CCT project 79
Figure 4-1 Overview of the synchronisation process 102
Figure 4-2 Schematics of the protocols and their activities or subsystems 103
Figure 4-3 Clean water experimental procedure simulating a family of five ... 106
Figure 4-4 Experimental procedure for inputting on solids deposit 108
Figure 4-5 Temperature profiles of liquids streams across process 1 and 2 .. 111
Figure 4-6 TP's visual observation of toilet paper conveyance 113
Figure 4-7 CP's visual observations of toilet paper conveyance 114
Figure 5-1 Integrated knowledge transfer framework 127

List of Tables

Table 1-1 Examples of university-industry collaborations 2

Table 1-2 Framework of partner roles across TRLs adopted by the BMGF for NSSS development 5

Table 2-1 Activities involved in the field testing campaigns 26

Table 2-2 Overview of feedback points from both field testing campaigns 29

Table 2-3 Adapted Gioia method 29

Table 2-4 Division of labour across field testing activities in India 33

Table 2-5 Division of labour across field testing activities in South Africa 34

Table 3-1 Environment, stage of development, and fidelity per TRL 54

Table 3-2 Technology development partners and their roles within the project 59

Table 3-3 Supporting literature for the ERDE stages 63

Table 3-4 Populated improvements log with project data 69

Table 3-5 Examples of aggregated improvement points 78

Table 4-1 Overview of key process metrics from the clean water experiment 109

List of Abbreviations

BMGF	Bill & Melinda Gates Foundation
CCT	Cranfield Circular Toilet
CP	Commercial Partner
DD	Double Diamond
EP	Engineer Partner
ERDE	Experimenting, Reviewing, Distributing, Executing
FTT	Field Test Team
IKTF	Integrated Knowledge Transfer Framework
ILT	Improvement Log and Tracker
IN	India
IOC	Improvement Observation Card
IP	Intellectual Property
MD	Membrane Distillation
MURT	Multi-User Reinvented Toilet
NSSS	Non-Sewered Sanitation System
PM	Project Manager
PMC	Presentation Metadata Card
R&D	Research and Development
RTTC	Reinvent the Toilet Challenge
SURT	Single-User Reinvented Toilet
TD	Technology Developer
THC	Technology Holding Company
TM	Third Mission
TP	Technology Partner
TRL	Technology Readiness Level
TTO	Technology Transfer Office
TTP	Technology Transfer Professional
UIC	University-Industry Collaboration
VoD	Valley of Death
WSH	Water, Sanitation, and Hygiene
ZA	South Africa

1 Chapter 1: Introduction

1.1 Research Background

University-industry collaborations (UICs) are increasingly viewed as important drivers in the modern innovation landscape (Ankrah & Al-Tabbaa, 2015; Rossoni et al., 2023). Though diverse in their nature (Perkmann et al., 2013), these partnerships often seek to provide a pathway between academic research and practical application, facilitating the transfer of cutting-edge outputs into tangible, market-ready solutions (Sarpong et al., 2023). While UICs have a long history, their importance continues to evolve as influenced by global trends in open innovation (Bejarano et al., 2023), innovation ecosystems (Heaton et al., 2019), and rising expectations for both academia and industry to address societal grand challenges (Bodley-Scott & Oymak, 2022).

Within this landscape, the concepts of knowledge transfer and technology transfer play crucial roles. Knowledge transfer in UICs encompasses a range of activities through which information, skills, and expertise move between partners (Alexander et al., 2020). It has also been referred to as "the multiple ways in which knowledge from universities can be exploited by industry in order to create economic, social value and competitiveness" (Ferreira & Carayannis, 2019, p. 353). Technology transfer, often considered a nuance of, or in conjunction with, knowledge transfer (Lockett et al., 2008; Vick et al., 2018), is referred here as a more formalised process of transferring tangible research outputs (e.g., patented inventions) from academic institutions to industry partners; typically involving legal mechanisms such as licensing agreements (Bozeman, 2000; Siegel et al., 2004). While academic literature explores further nuances in the relationship between knowledge transfer and technology transfer (Gopalakrishan & Santoro, 2004; Ismail et al., 2018), with many authors using them interchangeably or in tandem as 'knowledge and technology transfer', this thesis focuses on these broader definitions as they directly relate to the development and commercialisation of novel technologies in UICs. In this context, the initial 'technology transfer' serves as a catalyst for ongoing, technology-focused knowledge exchange as the partners collaborate to solve problems, advance the

technology, and drive innovation towards practical application; even in the presence of complex intellectual property considerations (Lockett et al., 2008).

The increase in interaction between universities and industry has given rise to terms such as ‘academic entrepreneurs’ (Bercovitz & Feldman, 2008) and the ‘entrepreneurial university’ (Etzkowitz et al., 2000). These concepts relate to academia adopting an entrepreneurial culture and interfacing with industry through various channels (e.g., contract research and licensing) to facilitate the transfer and commercialisation of research outputs for real-world impact (i.e., exploration *and* exploitation; Chang et al., 2016). This has led to universities adapting to what is known as the Third Mission (Compagnucci & Spigarelli, 2020), which expands beyond their traditional roles of teaching and research towards grappling and engaging with socio-economic challenges; solidifying themselves as key actors in both regional and global innovation ecosystems (Cai et al., 2020).

Examples of academic-industrial collaborations can be found across the globe and within several different sectors. Table 1-1 presents a snapshot of several different partnerships, demonstrating the wide range of fields impacted. Though not exhaustive, these partnerships reflect modern collaborative efforts towards addressing complex societal issues and steering the latest technological advancements. Additionally, Table 9 from the *Global Innovation Index 2023* (WIPO, 2023) highlights leading examples of academic-industrial collaborations within top global science and technology clusters.

Table 1-1 Examples of university-industry collaborations

University	Industry Partner	Collaboration Focus	Reference
Massachusetts Institute of Technology (MIT) (USA)	IBM	Artificial Intelligence	MIT News Office (2017)
University of Cambridge (UK)	AstraZeneca	Genomics	University of Cambridge (2023)
University of Sheffield (UK)	Boeing	Aviation	University of Sheffield (2022)

Swinburne University of Technology (Australia)	Siemens	Green Energy	Swinburne University of Technology (2023)
Nanyang Technological University (Singapore)	Volvo	Autonomous Vehicles	Nanyang Technological University (2018)

The motivation for collaboration between these two entities are wide spread but limited here to aspects of technology development and commercialisation. For universities, industrial partnerships can offer new streams of income to continue their research, provide real-world experiences for their personnel, and enhance the impact, relevance, and practical application of their research outputs (D'Este & Perkmann, 2011). Industry is motivated by the chance to access specialised knowledge and cutting-edge technology, reduce R&D costs and associated risks, and gain a competitive edge through innovation (Ankrah & Al-Tabbaa, 2015). Ultimately, both partners are looking to utilise the others' resources and capabilities in a complementary manner (Rajalo & Vadi, 2017). This is particularly the case whereby more complex targets (e.g., Sustainable Development Goals) demand and encourage such interdisciplinary approaches (Trencher et al., 2014; Bodley-Scott & Oymak, 2022).

Nonetheless, collaborations between universities and industry are not without their challenges. This is primarily a result of their deep rooted institutional differences which bring forward divergent goals and cultural norms (Bruneel et al., 2010). Universities, grounded in knowledge generation and the pursuit of academic excellence, often prioritise long-term, societally impactful research goals. Conversely, industry entities are primarily profit oriented, focusing on short-term, market-driven outcomes. These differences can lead to conflicts in priorities and expectations within collaborative projects, challenges that can be further exacerbated in international collaborations.

In the realm of technology development, university and industry partners, although complementary on paper, are naturally positioned on opposite spectrums of the Technology Readiness Levels (TRL) scale (Mankins, 2009;

Pujotomo et al., 2023). While universities excel in fundamental research and proof-of-concept (lower TRLs), industry favours more tangible, late-stage technologies with proven commercial viability (higher TRLs). The gap between these positions is often referred to as the “Valley of Death” (Ellwood et al., 2022), a critical phase where promising innovations struggle to transition from lab-scale research to market-ready products. This challenging landscape often impedes the progression of potential innovations, highlighting the need for effective strategies to bridge the divide between academic discovery and industrial application.

1.1.1 Research Environment

The global sanitation crisis emerges as a critical example within this challenging landscape. This grand challenge, captured in the United Nations Sustainable Development Goal 6, which targets clean water and sanitation for all by 2030 (United Nations, 2023), illustrates a societal inequality that underscores the pressing need for collaborative action between universities and industry to transform pioneering research into practical, life changing solutions.

An estimated 3.5 billion people across the globe lack access to safely managed sanitation services, with approximately 1.5 billion lacking even basic services (UNICEF, 2023). The consequences pose significant socio-economic challenges related to illness, disease, death, and loss of productivity. Ensuring global access to safely managed toilets has been forecasted to generate $86 billion annually through greater productivity and reduced health costs, improve school and work attendance by three billion days each year, and unlock $420 billion in productive value (WaterAid, 2021). Moreover, the forthcoming global sanitation revolution gives rise to significant market opportunities within the emerging Sanitation Economy (Toilet Board Coalition, 2017).

A pioneering example of collective action addressing this challenge is the Bill & Melinda Gates Foundation’s (BMGF) Reinvent the Toilet Challenge (RTTC) initiative. Launched in 2011, the RTTC aims to incentivise innovations in toilet design and sanitation technology, aligning with the UN Sustainable Development

Goal 6.2—which relates to providing access to adequate, equitable, and safely managed sanitation for all by 2030 (Bill & Melinda Gates Foundation, n.d.a).

The RTTC focuses on the development of non-sewered sanitation system (NSSS) – revolutionary off-grid waste treatment solutions that operate independently of centralised water and sewage connection, using minimal electricity. These systems process human waste on-site into safe, manageable byproducts, transforming liquid waste into recyclable water and solids into pathogen-free bioresidue (Kone, 2023). The aim is to allow developing nations to leapfrog past traditional sanitation infrastructure and adopt sustainable, cost-effective decentralised waste treatment systems.

Operating within a complex network of collaborators, the RTTC often employs a specific nomenclature to delineate key partner roles. ‘Technical (or technology) partner’ (TP), ‘engineering partner’ (EP), and ‘commercial partner’ (CP) are terms used to distinguish the main responsibilities within this ecosystems. TPs are primarily responsible for conceptualisation, fundamental research, and initial technology development, and are often universities, though not exclusively. EPs, when applicable, support to bridge the gap between proof-of-concept and initial manufacturable design. CPs, suitable primarily for industry, are involved in the handover and product development towards commercialisation. These roles typically align with different stages of technology development, as illustrated in Table 1-2.

Table 1-2 Framework of partner roles across TRLs adopted by the BMGF for NSSS development

TRL Stage	TRL Level	TRL Definition	Conducted By
Research & Development	1	Basic principles observed and reported	TP
	2	Technology concept and/or application formulated	TP
	3	Analytical and experimental critical function and/or characteristic proof-of-concept	TP

Technology Demonstration	4	Component validation in laboratory environment	TP
	5	System/subsystem model or prototype demonstration in a laboratory environment	TP or EP
	6	System/subsystem model or prototype demonstration in a relevant environment	TP in collaboration with EP and/or CP
	7	System prototype demonstration in an operational environment	Led by CP with TP support (or EP)
Production & Deployment	8	Actual system completed and qualified through test and demonstration	CP
	9	Actual system proven through successful product launch	CP

However, it is important to note that the actual involvement of partners can be more fluid and project-specific than this framework suggests. This core structure is frequently supplemented by additional collaborators from both academia and industry, contributing specialised expertise, facilitating field-testing, or providing market and regional insights at various stages of development. The diversity and complexity of these collaborative arrangements reflect the multidimensional nature of the global sanitation challenge.

Collaborations within the RTTC are driven by several factors. The complexity of developing next-generation sanitation technology requires interdisciplinary expertise that transcends the capabilities of any single institution, whether academic or industrial. Given the global scale of the sanitation crisis, solutions must be adaptable to a wide range of cultural, economic, and environmental contexts, which necessitates diverse perspectives and knowledge. The potential for significant social impact—improving health outcomes and quality of life for millions—provides a shared goal that aligns the interests of both academic researchers and industry innovators. Furthermore, as the orchestrators of the initiative, the BMGF actively facilitate partnerships between diverse stakeholders to drive forward their mission.

Nonetheless, this collaborative environment faces significant challenges, particularly in navigating the “Valley of Death”. In the context of developing sanitation technology, this critical phase is characterised by multiple complex factors. These include the need for extensive field testing in diverse environments, compliance with stringent standards (e.g., ISO 30500) and complex regulatory approvals across different countries, and adaptation to varying user needs and cultural contexts. Additionally, ensuring robustness and scalability of the technology, translating early-stage prototypes into production-ready designs, and managing intellectual property across global partnerships present further hurdles. The international scope of these collaborations adds additional layers of complexity, requiring navigation of differences in languages, time zones, and business practices (Duan et al., 2010; Kalantaridis et al., 2017).

The BMGF, acting as a philanthropic venture capitalist, has invested over $200 million in research and development since the start of the RTTC, and has since pledged another $200 million for further refinement and market development (Bill & Melinda Gates Foundation, n.d.b). While this funding has led to many breakthrough inventions across the globe (see American National Standards Institute, n.d.), there has still yet to be a significant commercial breakthrough that has touched the lives of those who need this technology the most. Instead, many NSSS still struggle with challenges related to affordability, manufacturability, and scalability.

This landscape presents opportunities for in-depth research into the dynamics of international university-industry collaborations in their endeavour to develop and handover novel sanitation technology. The urgency of these efforts is underscored by the United Nation’s recent statement that achieving universal sanitation coverage by 2030 requires a five-fold boost of progress in sanitation development and deployment (United Nations, 2023).

1.2 Aim and Objectives

The aim of this thesis is as follows:

To develop and propose a knowledge transfer framework that facilitates international university-industry collaboration in the pursuit of the development and commercial handover of novel sanitation technologies.

To achieve this aim, four objectives were devised:

Objective 1 (Learn): An immersive exploration of an international university-industry collaboration to generate practical insights and recommendations for the field testing of novel sanitation technology.

Objective 2 (Create): To develop and apply a conceptual process framework for facilitating effective technology development and knowledge exchange in international university-industry partnerships targeting the advancement of novel sanitation technology.

Objective 3 (Align): To develop experimental protocols and analyse performance data to understand and enhance technology and knowledge synchronisation among international university-industry partners collaborating on the development of novel sanitation technology.

Objective 4 (Synthesise): To synthesise and integrate findings from three distinct studies to construct a cohesive narrative that contributes towards the underpinnings of a knowledge transfer framework for international university-industry collaborations in the realm of novel sanitation technology development.

1.3 Research Methodology

This thesis presents an integrated investigation of knowledge transfer in the context of international UICs focused on the development and commercial handover of novel sanitation technology. It synthesis methodologies and findings from three distinct yet interconnected chapters, each exploring different aspects of the collaboration process, and discusses them as an integrated framework to which each chapter feeds from the previous to outline a sequential narrative across the studies.

The complex nature of international UICs required a flexible yet structured research approach. This complexity is extended by the dynamic nature of

technology development projects, which often require adaptable methodologies. Following an overarching mixed methods approach, each research chapter offers a unique perspective or application utilising case studies:

1. Chapter 2 explores field testing coordination within an international RTTC community, employing a comparative case study approach to analyse team dynamics and operational best practices. This study served as the researcher's introduction to the complex landscape of international technology development collaborations.
2. Chapter 3 expands the focus beyond field testing to overall technology development, introducing the ERDE (Experimenting, Reviewing, Distributing, Executing) process framework and complementary digital artefacts. It utilises a single in-depth case study within a more specific international UIC to examine its effectiveness in coordinating dispersed technology development efforts.
3. Chapter 4 addresses synchronisation challenges identified through reflections on Chapter 3. The study implements and analyses an empirical synchronisation protocol within the same context.

The overall research process follows an inductive approach, moving from specific observations and findings in each chapter towards the development and proposal of a broader, more generalised knowledge transfer framework for technology development and handover within international UICs. This inductive process allowed for the emergence of patterns and themes across the studies, informing the construction of the overarching framework.

To structure this multifaceted, multi-paper research, an adapted version of the Double Diamond (DD) framework was employed. The DD was originally created by the Design Council as a guiding framework to foster innovation through a design approach (Design Council, 2015). It emphasises divergent and convergent phases to discover, define, develop, and deliver practical solutions for complex challenges. Figure 1-1 presents the DD framework as adapted to this research from a thesis lens.

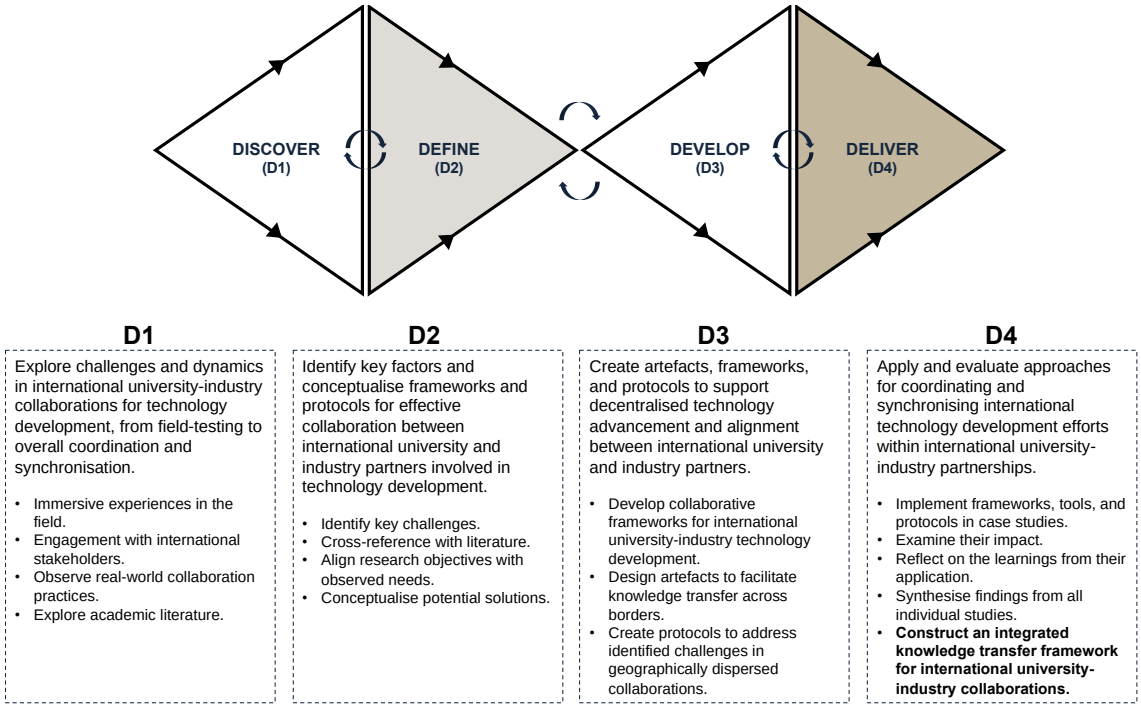

Figure 1-1 Adapted double diamond research methodology

While traditionally used in product and service development, the DD was adapted for this research for several key reasons:

1. The four phases of the DD align well with the progression of this research: initial exploration, understanding of challenges, development of frameworks and protocols, through to the synthesis into a knowledge transfer framework. This guiding structure provided a logical and compounding flow for investigating international UICs.
2. Much like product innovation, this research required both in-depth exploration (discover, define) and development of practical solutions (develop, deliver). This balance was crucial for addressing real-world issues in international UICs.
3. The DD's flexible structure accommodated different aspects of collaborative processes across the research. This adaptability was crucial in a fast-paced research environment, allowing the incorporation of mixed methods and responsiveness to emergent findings and evolving project requirements.

Other research methods were considered but ultimately discarded for this research. Grounded Theory, while valuable for theory development from

qualitative data (Corbin & Strauss, 1990), was not selected due to its lack of explicit phases for developing practical solutions, which were central to this research. Action Research, typically involving iterative cycles of intervention and reflection within a single organisational setting (Elden & Chishom, 1993), was deemed unsuitable due to the complexities of implementing and coordinating such an approach across geographically dispersed collaborations involving numerous, often conflicting, stakeholders. Compared to the DD, these methods did not offer the necessary balance of flexibility and structured progression required to address the multi-faceted nature of knowledge transfer in international technology development collaborations focused on sanitation technologies.

This overarching approach is designed to capture an in-depth understanding of factors affecting collaboration and innovation within geographically dispersed contexts, focusing particularly on the real world challenge of developing and transferring pioneering sanitation technology. By integrating the findings from each phase of the DD framework, the resulting knowledge transfer framework offers a comprehensive and practical understanding of the complexities involved; moving past the insights of each chapter alone.

1.4 Contributions of the Thesis

Scholarly and Practical: This research enhances the understanding of international university-industry collaborations (UICs) in technology development through several interconnected studies. The first study expands knowledge on field testing in cross-cultural settings by revealing the effectiveness of diverse team structures and capturing operational insights, thereby informing practices for geographically dispersed collaborations. It specifically highlights the viability of both small, focused teams and larger, decentralised teams in different cultural contexts. The second study introduces the novel ERDE (Experimenting, Reviewing, Distributing, Executing) process framework, which addresses the technology ‘Valley of Death’ by providing a structured approach to iterative development and knowledge exchange in decentralised contexts. This framework, along with its digital tools, contributes to innovation management and virtual coordination literature by offering practical mechanisms for capturing and

integrating multi-modal feedback from dispersed partners. The third study extends the understanding of alignment across cultural and institutional boundaries by examining the role of physical and digital boundary objects in synchronising technology and knowledge among dispersed partners. It provides insights into the challenges and successes of alignment between university and industry partners, emphasising the need for adaptive communication strategies. Finally, synthesising these elements, an integrated knowledge transfer framework is presented, offering a comprehensive approach to facilitating the complex dynamics of international UICs. This framework bridges a gap in the literature by focusing on micro-level interactions during the execution phase of UICs, providing both theoretical insights and practical guidance for navigating the challenges of decentralised development and subsequent alignment in cross-border collaborations. By addressing a range of technology development activities, from field testing through to synchronisation, this research contributes to both the theoretical understanding and practical management of knowledge transfer within international UICs, particularly in the context of developing technologies for diverse global markets.

Socio-Economic and Environmental: Many of the technologies primed to revolutionise the world and tackle global societal grand challenges often struggle to transition and scale from the laboratory into the real world for those who need them most. This intermediary stage where technologies are refined and transferred is crucial to realising this problem. The growing expectations on universities to contribute towards these societal challenges forms a reality where academic institutions must devise ways to effectively transfer their outcomes across institutional and international borders. This thesis delves into the intermediary stages of knowledge transfer within international university-industry collaborations for novel sanitation technology development. It proposes and uncovers strategies and challenges within this landscape, contributing to a greater understanding of how academic and industrial synergies can be harnessed to facilitate this crucial transition. The realisation of these reinvented toilet technologies will have profound effects on potentially billions of lives. Access to safe sanitation leads to improved health, stops the spread of disease,

reduces contamination of the environment, restores dignity to the people, and fosters economic development. Through the aforementioned, lifespan will be increased, pressure will be reduced on health care services, attendance will increase at schools and work, and new employment opportunities will arise through services.

1.5 Thesis Structure

This thesis follows the “Paper Format” style. It is structured as follows (Figure 1-2):

Chapter 1 introduces the thesis by outlining the research background, providing the aim and objectives, detailing the research methodology, summarising the contributions of the research, and mapping the thesis structure.

Chapter 2 conducts a comparative case analysis of two international field testing campaigns involving multiple geographically dispersed partners within an international RTTC community project. It focuses on team dynamics of the on-site field test teams across campaign activities and analyses valuable operational feedback to extract considerations for best practice within dispersed technology development collaborations.

Chapter 3 develops and applies a novel process framework aimed at coordinating decentralised technology development and knowledge exchange between international university-industry partners. It introduces three digital artefacts that facilitate connection between the different stages of the process and collect data. The process framework emphasises iterative, evidence-based refinements and multi-modal feedback to capture and address improvement points identified through various testing activities across partners. An in-depth case study is conducted on the Cranfield Circular Toilet which demonstrates its application.

Chapter 4 investigates synchronisation of knowledge and technology across international university-industry partners. It introduces a two-stage synchronisation process mediated by physical and digital boundary objects. That is, three replicas of a reinvented toilet system prototype and an operational protocol focused on its modular architecture embedded with experimental

procedures for measures of empirical synchronicity. The synchronisation process is contexed within a case study of the Cranfield Circular Toilet. It examines dynamics of knowledge and technology transfer across institutional and international borders.

Chapter 5 introduces a diamond-shaped knowledge transfer framework which synthesises the learnings from the previous chapters and integrates them into a cohesive narrative that forms the evolutionary linkage throughout the research. The framework proposes a dual-phased knowledge transfer approach of exploration and convergence. Key learnings and considerations are extracted.

Chapter 6 concludes the thesis through summaries of aim achievement, contributions to knowledge, and limitations and future research.

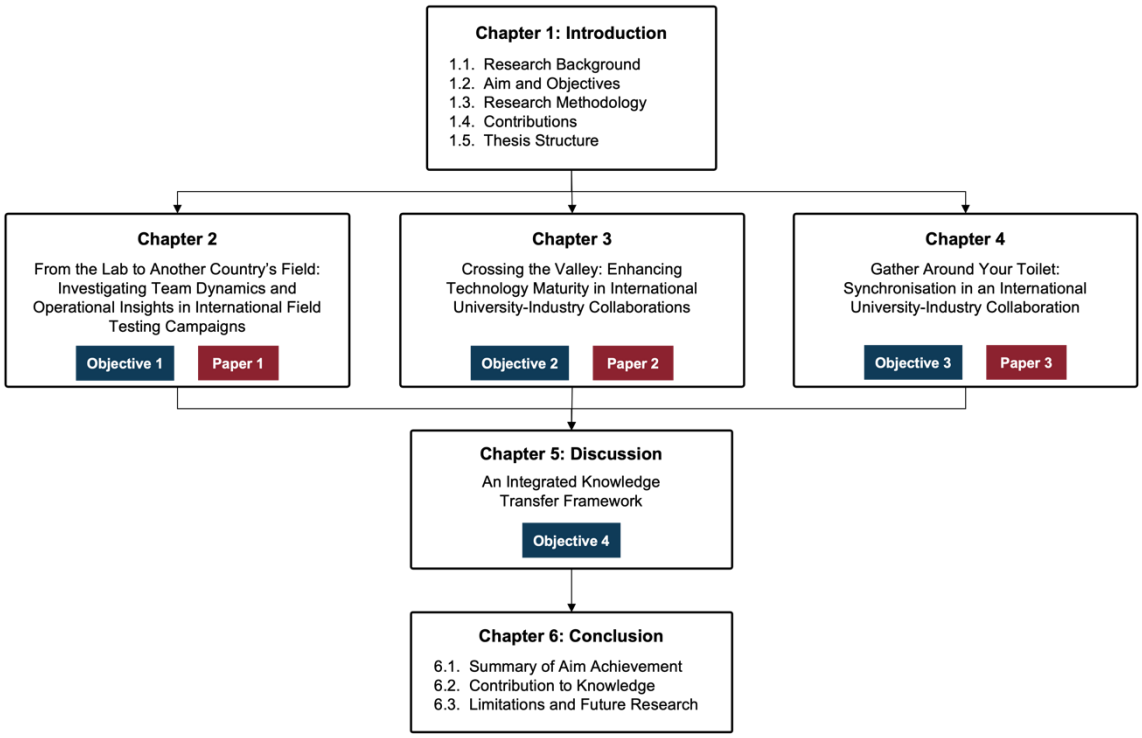

Figure 1-2 Illustration of the thesis structure

1.5.1 Papers Written as Part of Thesis

Three papers are embedded within the thesis. Harvey Fox is responsible for writing all sections, the development of the frameworks and tools, experimental protocols, data collection, and data analysis. Dr. Adriana Encinas-Oropesa and

Paul Lighterness were primary and secondary supervisors respectively and contributed through academic supervision: editing, feedback, and support. Other mentioned author contributions are related to funding acquisition, principal investigator, and co-investigator.

Paper 1 (Chapter 2):

Fox, H., Encinas-Oropesa, A., Lighterness, P., & Williams, L. (n.d.). From the lab to another country's field: Investigating team dynamics and operational insights in international field testing campaigns.

Paper 2 (Chapter 3):

Fox, H., Encinas-Oropesa, A., Lighterness, P., Collins, M., & Williams, L., (n.d.). Crossing the valley: Enhancing technology maturity in international university-industry collaborations.

Paper 3 (Chapter 4):

Fox, H., Encinas-Oropesa, A., Lighterness, P., Collins, M., & Williams, L., (n.d.). Gather around your toilet: Synchronisation in an international university-industry collaboration.

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2 Chapter 2: From the Lab to Another Country's Field: Investigating Team Dynamics and Operational Insights in International Field Testing Campaigns

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Abstract

This chapter explores team dynamics and practices in collaborative field testing of sanitation prototypes across international locations. A comparative case analysis is conducted on the first campaigns in South Africa and India involving university and industry partners. A mixed methods approach is deployed. Quantitative data examines team size and structure, division of labour across ten activities, and time taken to complete the campaign. Qualitative end-of-campaign feedback from project managers provides forward-looking perspectives. Findings reveal successful completion despite varying team sizes, with a core on-site group enabling coordination. Key dimensions enabling effective field testing include structured collaborative practices, data-driven design, regulatory and ethical compliance, localised technological adaptations, and community engagement. By building on prior work, this paper establishes an informative foundation for project managers undertaking rigorous collaborative testing of sanitation innovations. The results offer practical insights on harnessing global collaborations during critical field trials of solutions addressing pressing global sanitation needs.

Keywords: Field testing; non-sewered sanitation; university-industry collaboration; virtual teams; prototyping

2.1 Introduction

Field testing is acknowledged as an important step within the stages of new product development (Dolan & Matthews, 1993; Helm & Holly, 2000). The purpose of field testing is to introduce an early version of the technology, a high-functioning prototype, to an environment that closely resembles one in which it is intended to be deployed after commercialisation. This touches on technology readiness levels (TRLs) 5–7, where systems or subsystems are demonstrated in 'relevant' or 'operational' environments outside of the laboratory (Mankins, 2009). Testing within these uncontrolled environments allows the inventors of the technology to receive feedback on its operation; providing necessary learnings for adapting the technology towards productisation (e.g., user acceptance, robustness, and compliance to standards). As such, field testing serves as an important strategy for navigating the "Valley of Death" – the challenging phase where technologies transition from controlled environments towards demonstrating commercial viability (Markham et al., 2010). By resolving uncertainties through real-world demonstration and gathering user feedback in uncontrolled environments, field testing can significantly de-risk later commercialisation processes.

The field testing of non-sewered sanitation systems (NSSS) is often spoken about through a scientific, technical, or user experiential lens (Hennigs et al., 2019; Welling et al., 2020; Sutherland et al., 2021). These topics are critical to understanding the functionality of these breakthrough inventions, particularly their compliance with the stringent ISO 30500 standards (Cid et al., 2022). However, they often fail to acknowledge the 'behind the scenes' groundworks that occur in order to conduct and coordinate these activities.

A notable exception would be a recent paper by Sindall et al. (2021) who detailed the inner workings and lessons learned from operating the Engineering Field Testing Platform; a pre-commercialisation field-testing platform for innovative NSSS in Durban, South Africa. Here, the South African-based authors documented their learnings from testing 15 prototype sanitation systems across a range of environments and in collaboration with several international partners.

They detailed information on timelines, costs, activities, and lessons learned from over 3 years of practical experience.

Nonetheless, the authors only focus on one location, albeit a significant one in this context, leaving gaps in knowledge for how field testing occurs in other locations. Furthermore, although the authors focus on several critical variables related to project management (e.g., time and cost), they do not reveal much information at the team level. Variables such as team size and structure, as well as the division of labour across activities, provide a deeper understanding for how other researchers may need to equip themselves if they wish to conduct similar activities. Additionally, further research is needed to capture the voices of more field testing stakeholders (e.g., technology developers and other field testing locations) to contribute towards a more comprehensive understanding of conducting field tests on NSSS.

Building on prior work, this study undertakes an exploratory comparative case analysis of initial field testing campaigns conducted in India and South Africa. The analysis focuses on elucidating team dynamics and coordination practices by examining team size and structure, division of labour across key activities, timelines for completion, and end-of-campaign feedback from the field test teams and technology developer on improvements for future efforts. This multi-faceted investigation of the ‘behind the scenes’ elements aims to uncover insights and practical guidance for project managers undertaking collaborative testing of innovative solutions across international locations.

The remainder of the chapter is structured as follows: Section 2.2 provides an overview of the cases as well as the methods. Section 2.3 presented the empirical findings. Section 2.4 summarises the findings, discusses managerial implications, and addresses the limitations. Section 2.5 concludes the article.

2.2 Context and Methodology

This research adopts a comparative case analysis approach (Eisendhart, 1989; Yin, 2018) to explore the area of field testing novel sanitation technology within the context of a global collaboration involving multi-cultural partners across

institutions (e.g., universities and industries). A mixed methods approach is utilised (Johnson & Onwuegbuzie, 2004), focusing on team dynamics (size, division of labour, time taken) and constructive feedback for future campaigns. Specifically, it explores the first field testing campaign conducted at two international locations. Quantitative data provides measurable insights into teams and activities, while qualitative end-of-campaign feedback offers stakeholder perspectives on improvements. This comprehensive methodology serves to identify key challenges and learnings relevant to collaborative field testing across global sites.

2.2.1 Project Context

The context of this research is based within a large international collaboration formed to address the challenges proposed by the Reinvent the Toilet Challenge. The goal of this project is to create a sanitation system that processes human waste on-site (decentralised) without the need for mass sanitation infrastructure (centralised). At the time of data collection, there were over 10 organisations working towards the goals of the project. These comprised of various university and industry partners located across the globe. Their contributions were varied but united: universities were leveraged most for fundamental research, laboratory experiments, target-location field testing, and scientific consultancy, whereas industry contributed its expertise in product engineering and industrial design. There are, however, some nuances where ‘industry’ entities are more involved in the former than the latter, particularly within the realm of field testing.

This study focuses in on a specific area of the project and that is the field-testing of a subsystem prototype: the “frontend” of the toilet (Figure 2-1). This sub-system houses the user interface and pre-processing waste transportation mechanisms.

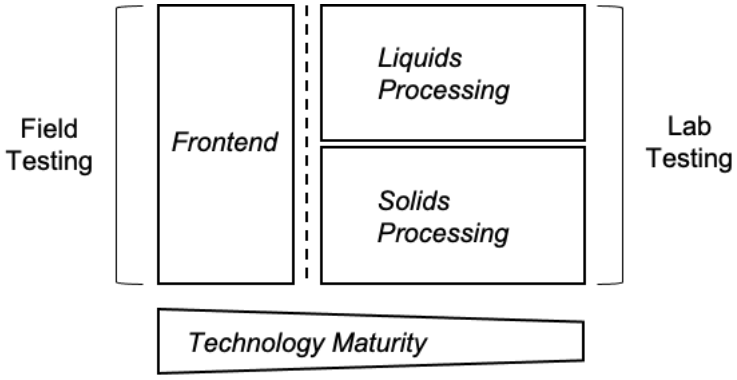

Figure 2-1 Basic diagram of subsystems

While all teams were aware of the field testing campaigns being conducted, not all of them were actively involved in the operations at this stage (Figure 2-2). They were, however, all informed and consulted.

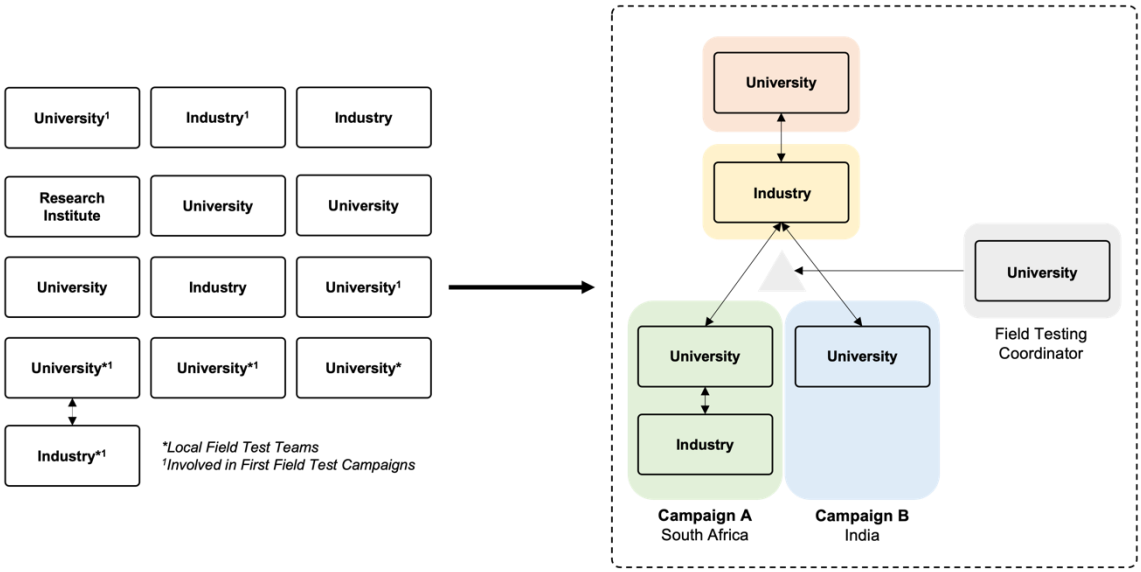

Figure 2-2 Project partners and those involved in field testing campaign

2.2.1.1 Field Testing Locations

The core target locations for the deployment of this technology are South Africa, India, and China. These regions offer pivotal opportunities for transformative improvements in sanitation and hygiene, directly benefitting public health and quality of life. Integrating the prototypes into these environments is an important step in the development and refinement of the technology.

In this case study, two field test locations are explored: one in South Africa and the other in India. The important distinction between these two locations is that South Africa is considered a “wiper” community (i.e., they use toilet paper for cleaning), and India is considered a “washer” community (i.e., they use water for cleaning). This has important implications for the waste treatment processes.

This was the first field testing campaign in both locations with this version of the technology. Initial preparations for a field testing site in China were in progress, but the site had not become operational within the data collection timeframe.

The timeline of the entire field testing campaign in South Africa was between July 2020 and February 2021, and between September 2020 and May 2021 in India. These field tests occurred during the global pandemic of COVID-19, which this led to its own set of difficulties (e.g., access to residency, laboratories, and equipment). Due to disruptions to international travel, it also meant that the majority of communication between the international teams was conducted online.

2.2.1.2 Activities Within a Field Testing Campaign

There are several activities that take place during a field testing campaign (Table 2-1). They are primarily conducted by the local field testing teams, but the decisions are formed in conjunction with the wider project partners (e.g., key performance indicators). These activities are what facilitates knowledge exchange as the consortia are leveraged on their varying expertise, be it local or subject specialist knowledge, to inform decisions being made, progression on the activities, and interpretation of the outcomes.

Table 2-1 Activities involved in the field testing campaigns

	Activity	Description
Preparation	Site selection	Members from the field testing team must liaise with the local community to find a suitable household that matches the criteria for testing the prototype. The residents of the house must be willing to install the prototype within their home and be receptive to disruptions and frequent interactions.

	Data collection plan	The specifics of how the prototype is going to be tested and what performance metrics are to be measured (e.g., sampling frequency).
	Ethics and documentation	An ethical application must be submitted to the local institution's ethics committee. This includes sign-off for both natural- and social-scientific testing (e.g., handling of hazardous materials, lab analysis, user consent, user feedback). Other documentation includes health and safety forms, operational manuals, and risk assessments.
	Site set-up	The preparation and physical installation of the prototype in the house. Residents will also receive an induction to the technology.
Execution	Sampling and analysis	The effluent from the prototype needs to be collected on-site at the residency and then transported to a laboratory for analysis.
Execution	End user feedback	Residents of the household are asked to complete survey questionnaires and to provide informal verbal feedback during site visits.
Execution	Site maintenance	Repairs to the prototype or modifications to the site (as and when needed).
Execution	Data sharing	Uploading the data to the project's online portal (e.g., scientific, social, photographs).
Evaluation	Decommissioning	Removing the prototype from the residency, restoring any modifications, and debriefing the participants.
Evaluation	End of campaign report	Producing a summary report detailing the process and learnings across the entire campaign to circulate to the wider project partners and stakeholders.

Note. The shipping of the prototype is not included here as the focus is on the activities from the perspective of the field testing team. The table attempts to represent sequential ordering, but many activities occur sequentially.

2.2.2 Data Collection

2.2.2.1 Quantitative Measures and Analysis

Team Size and Structure

Project managers (PM) from the field testing teams supplied organograms detailing team size and structure, role titles, and the number of entities (organisations) involved.

Division of Labour Across Activities

Data were obtained retrospectively post-campaign. The organograms were used as templates for the project managers to identify active team members across each of the ten field testing activities. 'Involvement' was defined at the PM's discretion and cross-verified by team leads.

Analysis metrics included:

- **Average involvement of individuals in each activity**: Calculated as the sum of involved individuals per activity, divided by the total number of activities.
- **Average number of activities per individual**: Calculated as the sum of each individual's activities, divided by the total number of team members.
- **Variability in individual activity involvement**: Measured using the standard deviation, calculated as: "Square root of [(Sum of (Each individual's total activities – Average tasks per individual) squared) / Number of team members]."

Time Taken to Complete the Campaign

Gantt charts, sourced from PMs, indicated the campaign duration and were cross-referenced with additional project documentation. Time measurement, abstracted to months, comes with the caveat that certain activities, like user feedback, are not suitable for this metric. Durations should be viewed as rounded approximations rather than exact figures.

2.2.2.2 Qualitative Measures and Analysis

Qualitative feedback was obtained through end-of-campaign summary report forms completed by project managers from the technology developer and field test teams. Respondents provided discrete comments in a tabular format with columns for source (team), lesson learned (short title), and detailed explanation. Non-generalisable technology and context-specific feedback were excluded, resulting in 20 feedback points split between the two field testing campaigns (Table 2-2). These were the input for the qualitative analysis described below.

Table 2-2 Overview of feedback points from both field testing campaigns

Campaign	Respondents	Initial Feedback Points	Feedback Points Removed	Feedback Points Included
South Africa	Project manager from field test team	11	1 (10)	14
	Project manager from technology development team	4	0 (4)	
India	Project manager from field test team	3	1 (2)	6
	Project manager from technology development team	9	5 (4)	

A Gioia-inspired approach (Gioia et al., 2013; Gioia, 2021) was used to analyse the 20 qualitative feedback points collected from the two end-of-campaign reports. The method was adapted to suit the structured nature of the feedback while maintaining analytical rigour. Table 2-3 summarises the key differences between the traditional method and the approach deployed here.

Table 2-3 Adapted Gioia method

Aspect	Traditional	Adapted
Data source	Interview transcripts	Discrete feedback points
Data volume and structure	Large, unstructured	Concise, pre-structured
First-order concept generation	Multiple raw data points may form a single concept	One-to-one relationship between raw data and concepts
Second-order themes	Researcher-centric, often closely tied to theoretical constructs	Data-driven, limited theoretical influence, closer to informant
Aggregation process	Highly abstract, strongly tied to theoretical constructs	More balanced between data-driven insights and theoretical constructs
Theoretical integration	Often aims to extend or build new theory	Facilitates dialogue between findings and existing literature

The analysis involved several stages. Each of the 20 raw feedback points were translated into a first-order concept, preserving the informant's voice. These concepts were then clustered based on semantic similarities. Second-order themes were derived through an iterative process of abstraction and refinement, where each cluster of first-order concepts were abstracted to a suitable theme that represented the semantic tone of the group. The resulting eight second order themes were then further aggregated into five broader dimensions (Figure 2-3).

This adaptation maintained the Gioia method's systematic approach to qualitative data analysis while accommodating the structured nature of the feedback data. The process allowed for a clear progression from raw data to more abstract concepts, which was suitable for analysing feedback from several dispersed stakeholders involved in collaborative international field-testing.

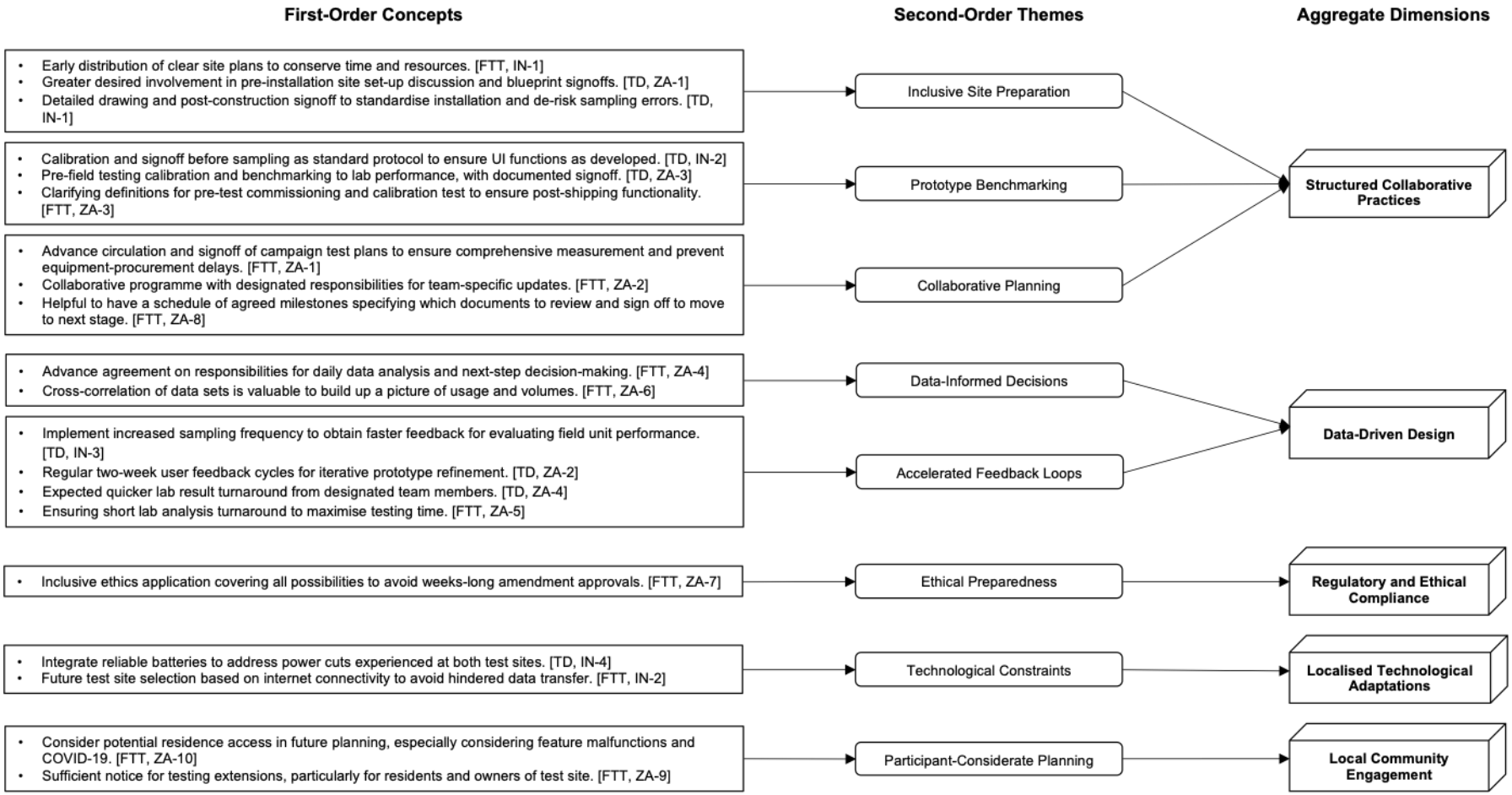

Figure 2-3 Data structure formed from field testing feedback

(TD = technology developer, FTT = field test team, IN = India, ZA = South Africa, *n* = initial sequential ordering of comments from end-of-campaign report minus those excluded; full code used for in-text cross-referencing)

2.3 Empirical Findings

2.3.1 Team Size and Structure

The South African team consisted of 22 members spread across four entities: ten in a local university, six in a local company, two as local government agents, and four as external contractors. In contrast, the Indian team had seven members from two entities: three from a local university and four as external contractors. For the purposes of this study, external contractors are considered as a single entity, regardless of their originating organisations. They are also distinguished from ‘industry’ partners in this context, as they were not disclosed to be another significant institution but more-so organised through the local fielding testing team. Furthermore, they were primarily involved in more labour-intensive activities, such as site set-up, maintenance, and decommissioning. Organograms detailing the team structures for the Indian team and South African team are shown in Figures 2-4 and 2-5 respectively.

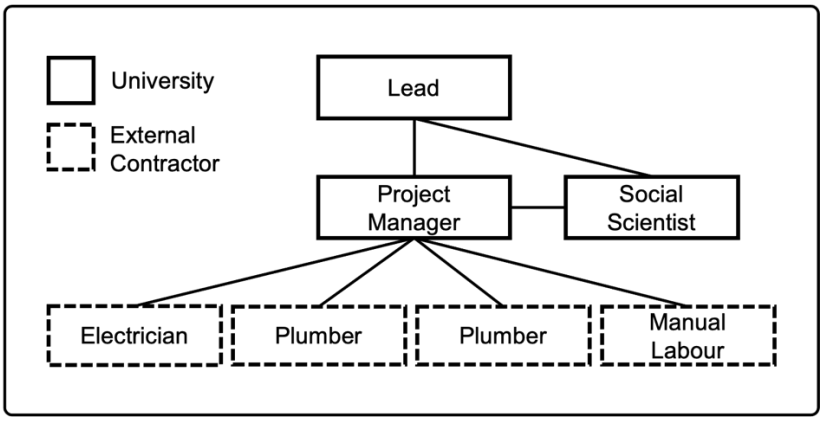

Figure 2-4 Organogram of the Indian field testing team

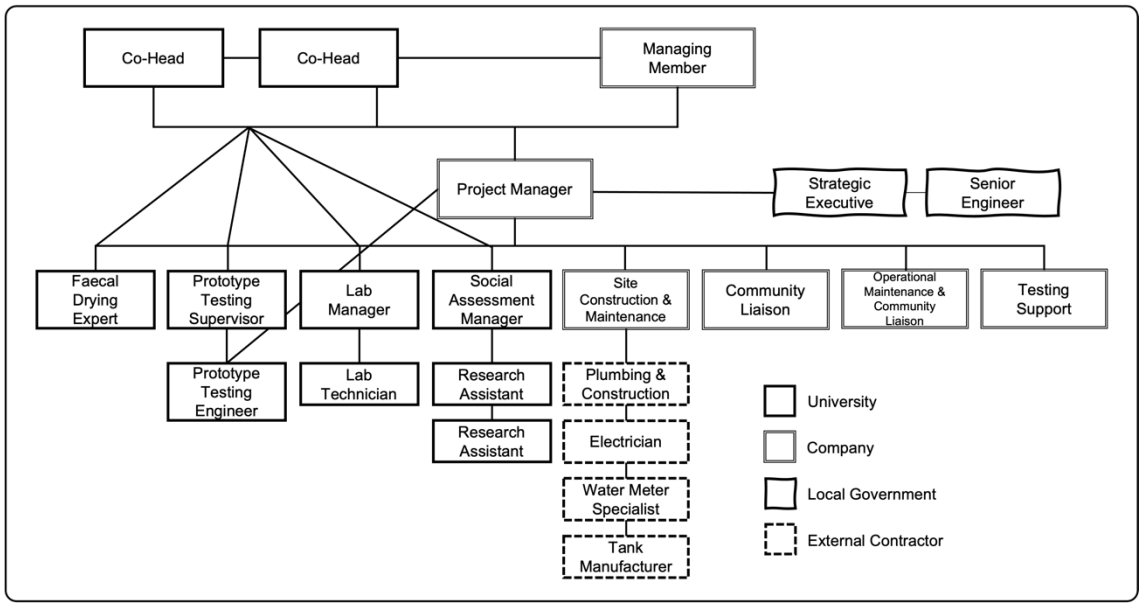

Figure 2-5 Organogram of the South African field testing team

2.3.2 Division of Labour Across Activities

The division of labour across the field testing activities for both the Indian and South African teams is detailed in Table 2-3 and 2-4, respectively. Key metrics were calculated to provide insights into the division of labour across both field testing teams.

Table 2-4 Division of labour across field testing activities in India

INDIA		**Field Testing Activities**										
Role	**Entity**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Total**
Lead investigator	University	✓	✓	✓							✓	4
Project manager	University	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	10
Social scientist	University		✓									1
Electrician	Contractor				✓			✓		✓		3
Plumber	Contractor				✓					✓		2
Plumber	Contractor				✓			✓		✓		3
Manual labourer	Contractor				✓			✓				2

Total	2	3	2	5	1	1	4	1	4	2	25

Table 2-5 Division of labour across field testing activities in South Africa

SOUTH AFRICA		**Field Testing Activities**										
Role	**Entity**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Total**
Co-head	University	✓		✓		✓			✓	✓		5
Co-head	University	✓	✓	✓			✓		✓	✓	✓	7
Faecal sludge expert	University			✓						✓		2
Prototype test supervisor	University	✓		✓		✓	✓			✓	✓	6
Lab manager	University			✓		✓						2
Social assessments manager	University	✓	✓	✓			✓			✓	✓	6
Prototype test engineer	University	✓	✓	✓		✓	✓	✓	✓	✓	✓	9
Lab technician	University			✓		✓						2
Research assistant	University		✓	✓			✓			✓	✓	5
Research assistant	University		✓	✓			✓			✓	✓	5
Managing member	Company	✓		✓	✓					✓		4
Project manager	Company	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	10
Site construction and maintenance	Company	✓		✓	✓			✓		✓		5
Community liaison	Company	✓	✓				✓					3
Maintenance and	Company		✓		✓	✓	✓	✓		✓		6

community liaison												
Testing support	Company				✓	✓		✓		✓		4
Strategic executive	Local Government	✓								✓		2
Senior engineer	Local Government	✓								✓		2
Plumbing and construction	Contractor				✓			✓		✓		3
Electrician	Contractor				✓			✓				2
Water meter specialist	Contractor				✓							1
Tank manufacturer	Contractor				✓							1
	Total	11	8	13	9	8	9	7	4	16	7	92

Average Involvement of Individuals in Each Activity

The South African team had an average of 9.2 individuals involved in each activity. In contrast, the Indian team had an average of 2.5 individuals participating in each activity. This indicates that the South African team had broader participation across activities, while the Indian team had more concentrated involvement.

Average Number of Activities per Individual

In the South African team, each individual was involved in an average of 4.2 out of 10 activities. On the other hand, individuals in the Indian team participated in an average of 3.6 activities. This suggests that while the South African team had more members involved in more tasks, the Indian team had fewer members who were also less diversified in their roles.

Variability in Individual Activity Involvement

The standard deviation, which measures how spread out the involvement is among the team members, was 2.4 for the South African team and 2.8 for the Indian team. This suggests a slightly higher variability in the Indian team, even

though it is smaller in size, indicating that roles might not be as evenly distributed as in the South African team.

Categorisation of Team Members: Peripheral, Medial, and Central

Upon further analysis, inspired by early research on team size differentiating between total team size (headcount) and 'functional' team size (active subset) (Bray et al., 1978), team members were categorised based on their involvement on their involvement across the 10 activities. Those involved in 1 to 4 tasks were classified as peripheral, primarily serving advisory or physical labour roles. Team members involved in 5 or more tasks were considered part of the core team, being integral to most project activities.

In the Indian team, there were 6 peripheral members and 1 core member. In contrast, the South African team comprised 12 peripheral and 10 core members. members. Therefore, the core team in India consisted of 1 individual (14.3%) whereas the core team in South Africa comprised of 10 individuals (45.5%).

2.3.3 Time Taken to Complete the Campaign

The South African campaign spanned eight months, while the Indian campaign lasted nine months (Figure 2-5). Specifically, the Indian team required more time for site selection (two months compared to one) and sampling and analysis (four months compared to three). The South African team took longer to complete the end-of-campaign report, requiring three months compared to India's two[1].

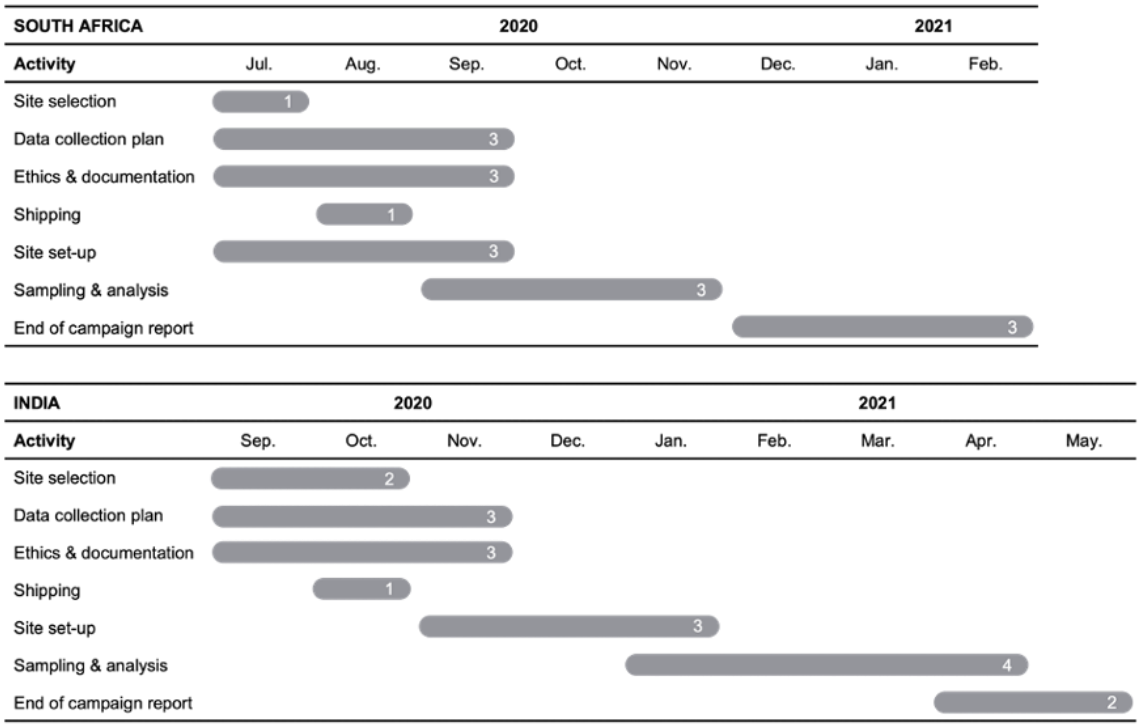

Figure 2-6 Gantt chart timelines of field testing campaigns

2.3.4 Qualitative Findings

As outlined in the data structure (Figure 2-3), concepts derived from the feedback provided by the project managers were inductively developed into second-order themes and aggregate dimensions. Based on the hierarchical abstraction process, the key themes arising from the informants' feedback are discussed, highlighting valuable insights into field testing prototypes across international locations.

Structured Collaborative Practices

Inclusive Site Preparation

Participants' feedback underscored the necessity for an inclusive approach during the early stages of site preparation. Distributing clear site plans well in advance was noted as critical to conserve both time and resources [FTT, IN-1]. The inclusion of the technology developer in pre-installation dialogues and blueprint approvals was also highlighted [TD, ZA-1]. Detailed drawings and post-

construction signoff emerged as key to standardising installations and mitigating sampling errors [TD, IN-1].

Prototype Benchmarking

Data reveals the pivotal role of rigorous benchmarking for prototypes. The technology developer advocated for calibration and pre-test signoff to ensure that the user interface functions as intended before sampling begins [TD, IN-2, ZA-3]. Additionally, the South African field test team recommended clarifying definitions for pre-test commissioning and calibration tests to ensure post-shipping functionality [FTT, ZA-3]. These insights collectively underline the multifaceted nature of prototype benchmarking in international collaborations.

Collaborative Planning

Feedback revealed preferences for more structured and cohesive planning mechanisms, particularly from the South African field test team. Advance circulation and signoff of campaign test plans emerged as a strategy for ensuring comprehensive measurements and preventing equipment procurement delays [FTT, ZA-1]. Having a collaborative program with assigned responsibilities for team-specific updates was also suggested [FTT, ZA-2]. Setting a schedule of agreed milestones specifying which documents to review and signoff before moving to a new stage was also mentioned [FTT, ZA-8].

Data-Driven Design

Data-Informed Decisions

The findings underscored the importance of making data-driven decisions through strategies like pre-agreeing on responsibilities for daily data analysis [FTT, ZA-4] and cross-correlating data sets to build a comprehensive understanding of usage patterns and volumes [FTT, ZA-6].

Accelerated Feedback Loops

Feedback from the field tests indicated the importance of fast feedback loops. Increased sampling frequency was recommended to obtain faster feedback for

evaluating field unit performance [TD, IN-3]. Regular two-week user feedback cycles were also advised for iterative prototype refinement [TD, ZA-2]. Other suggestions involved expecting quicker lab result turnaround from designated team members [TD, ZA-4] and ensuring a short lab analysis turnaround to maximise testing time [FTT, ZA-5].

Regulatory and Ethical Compliance

Ethical Preparedness

Ethical preparedness was identified as vital for avoiding approval delays. A comprehensive initial ethics application was recommended as a means to avoid time-consuming amendments [FTT, ZA-7]. This highlights the essential role of ethical considerations in field testing, a factor that cannot be overridden.

Localised Technological Adaptations

Technological Constraints

Adapting technological infrastructure to overcome local constraints was emphasises as crucial for successful field testing. Recommendations focused on integrating reliable batteries to combat power cuts experienced at both sites [TD, IN-4] and considering internet connectivity for future site selection to reduce hindered online data transfer [FTT, IN-2].

Local Community Engagement

Participant-Considerate Planning

The findings point to the importance of considering field-testing participants, particularly residents and site owners, in the planning and implementation stages. Specifically, the need to plan for potential access to residences is highlighted, particularly in light of unexpected feature malfunctions and COVID-19 restrictions [FTT, ZA-10]. Further, it is emphasised that sufficient notice must be given for any testing extensions to secure the agreement of those who will be directly impacted, notably the residents and site owners [FTT, ZA-9].

2.4 Discussion

2.4.1 Summary of Quantitative Findings

The quantitative findings reveal that the Indian field testing team involved seven members, with one individual considered the core central member based on involvement across the ten activities. In contrast, the South African team had 22 members, with ten classified as the core project team. Despite the size differential, both teams completed the structured field testing campaign with a similar timeframe. The Indian team took one month longer overall, but this difference is considered minor due to the extensive scope of the testing activities.

While the South African team engaged more individuals across its decentralised structure, the concentrated Indian team demonstrated that a small group built around an adept central member can effectively carry out the rigorous requirements of field testing prototype systems; at least within the timeline explored in this study. Whether such concentrated team structures are sustainable over multiple long-term campaigns without expanding to prevent burnout remains an open question outside the scope of this initial exploratory analysis.

The key implication is that field testing campaigns for technological systems can be successfully executed by teams of varying size and structure. However, while this offers initial insights, it is not exhaustive.

2.4.2 Summary of Qualitative Findings

The qualitative data provides forward-looking guidance on conducting international field testing campaigns. These insights are grouped into five pivotal dimension, each with its own set of underlying themes.

“Structured Collaborative Practices” underscores the importance of comprehensive planning mechanisms, an observation echoed in Sindall et al. (2021) about the value of upfront agreements and guidelines. This dimension involves ‘Inclusive Site Preparation,’ which advocates for clear site plans and inclusive dialogues; ‘Prototype Benchmarking,’ necessitating rigorous calibration

and pre-test signoff; and, crucially, ‘Collaborative Planning,’ which calls for structured and cohesive planning mechanisms amongst internationally dispersed teams.

The “Data-Driven Design” dimension focuses on the critical nature of data analytics in effective field testing. ‘Data Informed Decisions’ advocate for a pre-established framework for daily data analysis and the integration of multiple data sets for a holistic understanding of the units performance. ‘Accelerated Feedback Loops’ stresses the importance of agile systems that facilitate quick adaptations based on new data.

“Regulatory and Ethical Compliance” emphasises the proactive role of ‘Ethical Preparedness,’ advising project leaders to think about ethical considerations early on to avoid downstream delays due to amendment-related wait times. This highlights the importance of ethics not only as a regulatory must but also as a project management consideration.

“Localised Technological Adaptations” underscores the need for context-specific technological solutions. This resonates with Sindall et al.’s (2021) emphasis on localising technologies to the specific testing environment.

Finally, “Local Community Engagement” highlight the central theme of participant consideration in the planning and implementation of field tests. This thoroughly aligns with Sindall et al.’s (2021) emphasis on continuous community engagement throughout all stages of the field testing campaign.

In summary, the qualitative findings not only offer a forward-looking lens on field testing best practices, but they also resonate in various ways with Sindall et al. (2021). This serves to contextualise and deepen the academic discussion surrounding international collaborations in field testing.

2.4.3 Managerial Implications

This research reveals several valuable recommendations for project managers and field testing teams when coordinating the testing of prototypes across international site.

Thorough calibration and benchmarking against lab performance is advised before deploying prototypes to the field site. This ensures that the prototype is functioning as intended. Documented signoff should be obtained from all partners involved to ensure expected functionality. Protocols for site installation, data collection, analysis, and decision-making should also be agreed upon in advance to promote coordinated practices and workflows that aim to mitigate errors or delays when working with international teams.

Feedback loops are an essential part of field testing as the emerging data is critical for rapid iterative refinement of the technology. High sampling frequency as well as regular feedback from users should be a priority. Expect and plan for quick sample analysis turnaround times ensuring that the flow of information across dispersed team members is streamlined and timely.

Regulatory and ethical compliance is critical when conducting field tests. This for the protection of all stakeholders involved including the users. The drafting of the ethics application should involve all relevant partners to ensure that the document is comprehensive enough to avoid time-consuming amendment that can eat up valuable testing time.

Managers should be aware that each field testing site will come with its own set of constraints that have to be overcome or adapted towards. In this study, the experience of power cuts in South Africa and India warranted the inclusion of more reliable back-up batteries that would ensure the technology could keep running. Similarly, reliable internet connection for test sites was flagged as a future site collection criteria if continuous online data transfer was to be expected.

An essential part of field testing is the engagement with the community who have volunteered as participants to test and use the technology. Project partners may have their demands to keep the campaign running and obtain valuable insights. However, their expectations must be managed and aligned with the participants involved. Keeping the community engaged with the project and ensuring their willingness at all stages is critical.

A core field test team at the target location involved across most activities is recommended for coordination and continuity. Support this group with specialised peripheral members such as local construction crews. Sizeable groups can enable for broader participations across tasks, but teams should strive for balanced workloads. The findings here showed that considerably different team sizes could complete the same activities in near similar timelines. However, the question remains whether or not such a significant emphasis on only one or few persons alone is sustainable.

Ultimately, structured collaborative practices, accelerated feedback loops, ethical preparedness, localised technological adaptations, and community-inclusive planning will enable field test teams to strategically navigate the complexity of prototype testing involving international partners.

2.4.4 Limitations and Future Research

This study, while contributing valuable insights into international collaborations for field testing, comes with several limitations that suggest directions for future research.

Firstly, the study is constrained by its focus on a single field testing campaign in each of the two countries, South Africa and India. A longitudinal approach that tracks project progress and the evolution of team dynamics over multiple field testing campaigns could offer a more comprehensive understanding. This opens up avenues for future research to examine how team collaboration and efficiency evolve over time.

Secondly, the qualitative component of the research relies solely on discrete written feedback from project managers, introducing potential managerial bias. Future research could enrich these findings by incorporating interviews and perspectives from other team members, thereby ensuring a more comprehensive understanding of the collaborative dynamics.

Thirdly, the study addresses quantitative metrics, such as individual involvement and the number of activities completed, without addressing the quality of the work

produced. This leaves questions about performance and productivity unanswered.

Fourthly, given the context-specific nature of the study and its small sample size, the generalisability of the findings is limited. The insights provided may not extend to other technologies, testing scenarios, or cultural contexts. Therefore, the learnings should be applied cautiously and within the boundaries of similar circumstances.

Fifthly, the study uses retrospective self-reported data, which could introduce recall or interpretive bias, affecting the reliability of activity timelines and participation levels. Future research could mitigate this by employing real-time tracking methods, such as field observations and activity logs.

Finally, the activity involvement measures offer limited snapshots of complex team processes. Exploring interaction patterns and relational dynamics could provide deeper understanding of coordination within such teams. To further this, future research may also consider the impact of cross-cultural communication (e.g., language differences) on the efficiency of field testing activities.

2.5 Conclusion

This exploratory case analysis offers initial insights into team dynamics and practices for field testing sanitation prototypes across global sites. It revealed that successful campaigns can be executed by varying team structures if supported by a core group at the test location. Key findings underscore structured coordination, accelerated feedback, ethical preparedness, localised adaptations, and community inclusion as critical dimensions that should be considered for the successful management of the intricacies involved in international field testing. While limited as a snapshot study, it builds on prior work to provide forward-looking guidance grounded in stakeholder experiences for project managers undertaking collaborative field evaluations of breakthrough technologies. Further longitudinal research would enrich understanding of how team efficiency evolves over campaigns. Nonetheless, these insights establish an informative foundation

on harnessing global partnerships during the testing of innovative solutions for one of humanities greatest challenges.

Notes

1. The submission from the South African team coincided with a local holiday period which led to delays.

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3 Chapter 3: Crossing the Valley: Enhancing Technology Maturity in International University-Industry Collaborations

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Abstract

University-industry collaborations (UICs) are key in transitioning lab-based technology towards practical, real-world applications, addressing a significant development challenge known as the technology 'Valley of Death'. This chapter contributes to the existing discourse by introducing and applying a novel four stage process framework – Experimenting, Reviewing, Distributing, Executing (ERDE) – designed to facilitate collaborative technology advancement through iterative, evidence-based refinements. Through a detailed case study of the Cranfield Circular Toilet, a non-sewered sanitation system, this ERDE framework is examined. Three digital artefacts are introduced to facilitate execution across the stages and data collection. The findings illuminate the dynamics of process management and stakeholder engagement within international UICs focused on developing technologies that meet societal needs. This pragmatic approach offers benefits for managing technology development in complex collaborative settings.

Keywords: University-industry collaboration; technology Valley of Death; innovation management; virtual teams; prototyping

3.1 Introduction

University-industry collaborations (UICs) are increasingly recognised for their potential as key drivers for creating technological innovations that address socio-economic and environmental challenges (Audretsch, 2014; Fini et al., 2018; Mascarenhas et al., 2018; Sarpong et al., 2023). The synergistic blend of academic investigation and industrial pragmatism contains a unique potential to transition new scientific discoveries into impactful commercially viable products. Nonetheless, despite these promising intersections, the scholarly literature has underscored the inherent frictions within UICs – notably, divergent objectives, management styles, and organisational cultures – that often hinder the very innovation they strive to foster (de Wit-de Vries et al., 2019; O'Dwyer et al., 2023). These challenges can be exacerbated when UICs undertake ambitious research targets, which are inherently characterised by ambiguity and uncertainty (Morandi, 2013). Hence, aligning their endeavours is essential for realising the potential outcomes.

University and industry partners typically differentiate their innovation stages, focusing on distinct stages of the Technology Readiness Levels (TRLs) framework (Mankins, 2009). Universities specialise in conducting fundamental research and reaching proof-of-concept for their innovative breakthroughs, usually up to TRLs 3–4. In contrast, industry focuses on the latter stages, particularly TRL 7–9, steering the production and commercialisation of these innovations. Bridging this gap, a recurrent dilemma in innovation policy (e.g., UK Government, 2013), remains critical, as it represents a stage where promising technologies often lay dormant. This gap is colloquially referred to as the Valley of Death (VoD), a metaphorical landscape characterised by high uncertainty and risk, which causes many projects to stall due to a lack of feasible validation and assigned funding (Frank et al., 1996; Markham et al., 2010).

The concept of the VoD in innovation is traditionally associated with a focus on financial investment as a primary means of support (Frank et al., 1996; Auerswald & Branscomb, 2003). However, this monetary focus is now recognised as part of a broader spectrum of necessary interventions. Alternative approaches, such as

the strategic role of intermediaries (Islam, 2017), serve as an example of the multifaceted factors that also facilitate technology maturation.

As investigations into various strategies to navigate the VoD in innovation continue to unfold, UICs can still face challenges in identifying and implementing effective approaches to steer the intermediate phases of technology development. This nuanced direction is essential for the maturation of technologies towards market readiness. Although there are valuable insights to be drawn from related domains such as academic entrepreneurship (Aydemir et al., 2022), technology transfer (Siegel et al., 2004), proof of concept centres (McAdam et al., 2009), and knowledge transfer partnerships (Wynn & Jones, 2017), they often fall short of addressing the VoD with a precise focus on the technological advancements made within UICs, especially when considering large-scale international collaborations. Meanwhile, the few studies that do focus on the VoD within UICs primarily consider the roles of technology transfer personnel and technology holding companies (Takata et al., 2022; Son et al., 2022), and not the intricate, collaborative processes needed for technological maturity. These papers predominantly concentrate on variance approaches or offer guidelines centred around high-level programme support. While such guidance can be widely applied, it often overlooks the intricate processes necessary for advancing a technology's maturity.

The landscape of literature on innovation processes specifically designed to support UIC endeavours in bridging the 'technology development' VoD is not well chartered. A notable exception is a recent paper by Ellwood et al. (2022), who offered a conceptual framework composed of five key iterative innovation processes critical for crossing the VoD. In their introduction, the authors remarked that "there is no current explanation of the innovation processes for crossing the Valley of Death" (Ellwood et al., 2022, p. 3). This lack of guidance on the practical innovation activities presents an opportunity for researchers to delve deeper into investigating and proposing processes involved in traversing the technological VoD.

This study develops and examines the application of a process framework designed to demonstrate technology maturity through evidence-based iterations within an international university-industry collaboration traversing the technological VoD. It adopts an in-depth, single case study methodology to provide a detailed account of the proposed framework in action. While valuable insights can be drawn from related research on intermediary roles, financing, and other factors, there remains a need for in-depth investigation of the practical innovation activities and knowledge exchange mechanisms that enable collaborators to jointly navigate this high-risk phase. By exploring the development, implementation, and impacts of this process framework, this study seeks to address this gap and contribute new insights on facilitating technology maturity in dispersed university-industry partnerships. The examination of the framework's stages, application, and outcomes aims to enrich available guidance for innovators navigating the VoD.

The rest of the chapter is structured as follows. Section 3.2 explores the theoretical background. Section 3.3 introduces the context and methodology. Section 3.4 outlines the process framework. Section 3.5 demonstrates its implementation. Section 3.6 presents the discussion. Section 3.7 concludes.

3.2 Theoretical Background

3.2.1 University-Industry Collaboration and Technology Development

Universities are now expanding beyond their traditional teaching and research roles to engage with the wider society through what is known as the "Third Mission" (TM) (Etzkowitz et al., 2000; Compagnucci & Spigarelli, 2020). The TM represents a significant shift for universities to become more entrepreneurial, collaborate with industry, commercialise research, and foster socio-economic development. The practical realisation of the TM can often take shape through university-industry collaborations (UICs). UICs are unique in three ways: they bring together professionals from academia and business, involve collaboration between individual members or teams rather than entire firms, and often occur

across different organisations, meaning that not all collaborators are from the same institutional background (Amabile et al., 2001).

UICs manifest in many different forms (Perkmann et al., 2013). The literature distinguishes between formal and informal channels of UICs (Fabiano et al., 2020). The former refers to activities which are regulated through contractual agreements aimed at exploiting knowledge, technology, and expertise. Examples include joint research and development (R&D) projects, spin-offs, and technology licensing. The latter concerns interactions that are more casual, non-contractual, and often centre around existing capabilities and knowledge that are not easily protected by patents. Examples consist of consultancy and conferences.

Focusing on formal channels, UICs play an important role in driving innovative R&D across various industries, contributing to the progression of new technologies and solutions (Cohen et al., 2002). A critical aim is to leverage the complementary capabilities and resources of academia and industry to advance the technological maturity of emerging innovations.

Firms are motivated to collaborate with universities as a means of accessing external sources of innovative knowledge and cutting edge technology that create competitive advantages in their markets (Kauffman & Tödtling, 2001; Mascarenhas et al., 2018). In cases where firms encounter failure in their internal R&D projects, Slavova (2023) highlights the value of licensing-in technologies from universities as a strategic approach to enhance their innovation output and recover from previous setbacks. On the other hand, universities embrace the opportunity to test academic research in practical settings and gain valuable new insights to extend their core research activities (Lee, 2000). Furthermore, Fini et al. (2022) found that exploratory and entrepreneurial activities prompted by these collaborations can create a positive feedback loop, linking academic entrepreneurship back to impactful scientific research and the foundational mission of the university.

Despite the benefits, UICs frequently encounter challenges during their implementation that impede the advancement of technology maturity and hinder commercialisation efforts. Bruneel et al. (2010) distinguish between orientation-

related barriers, which encompass differences in incentives and working practices, and transaction-related barriers, which involve conflicts over patents, intellectual property rights, and regulations. These challenges create a complex landscape between the lab and the market (Battaglia et al., 2023).

While intermediaries like proof-of-concept programs (Battaglia et al., 2021) and technology transfer offices (Siegel et al., 2004) aim to navigate these challenges, many promising technologies still struggle to mature and bridge the gap from research to commercial viability. This persistent challenge, frequently referred to as the 'Valley of Death,' leaves many projects stranded and unable to contribute towards the TM. A deeper exploration of this notorious bottleneck follows.

3.2.2 The Valley of Death

The Valley of Death (VoD) refers to a nebulous landscape in the innovation process between invention and commercialisation where the feasibility of a new technology for market success remains uncertain (Frank et al., 1996; Auerswald & Branscomb, 2003). This phase poses significant challenges, as innovators must demonstrate the technology's practical applicability and readiness for market introduction. Moreover, the VoD represents a significant transition in funding sources, typically moving from public sector research grants to more outcome-oriented private sector investors who demand clear paths to profitability and market integration. In summary, the VoD is characterised by uncertainties around real-world applicability, commercial preparedness, and securing necessary financial backing.

The VoD has been examined across diverse contexts, including university-industry collaborations (Takata et al., 2022; Son et al., 2022; Hansen et al., 2022), start-ups (Gbadegeshin et al., 2022; Lefebvre et al., 2022), and large established firms (Dean et al., 2022; Midler, 2019). Numerous perspectives have also been applied to investigating the VoD directly or loosely. Notable examples include financing challenges (Auerswald & Branscomb, 2003; Beard et al., 2009), role theory dynamics (Markham, 2002; Markham et al., 2010), technology transfer offices (Brantnell & Baraldi, 2022; Takata et al., 2022), technology holding companies (Son et al., 2022), design approaches (Liedtka, 2015; Klitsie et al.,

2019), building investor trust (Lefebvre et al., 2022), the role of intermediaries (Islam, 2017; Bonnin Roca & O'Sullivan, 2022), product complexity (Dean et al., 2022), and innovation processes and management practices (Ellwood et al., 2022; Midler, 2019).

3.2.2.1 Valley of Death and Technology Readiness Levels

Technology Readiness Levels (TRLs) provide a structured scale to gauge the maturity of a technology (Mankins, 2009; Olechowski et al., 2015). Spanning from 1 to 9, each level signifies a progressive step in a technology's journey from its conceptual inception (basic research) to its full-fledged application in a real-world environment (commercial deployment). The TRL scale has been widely adopted by funding bodies to guide their investment priorities. For example, the European Union (EU) applied the TRL scale in both their previous Horizon 2020 and current Horizon Europe programmes. This helps to allocate funding to projects that aim to advance technologies to middle or high TRL levels, with the intention of transitioning promising research results into practical applications (Klessova et al., 2023).

Within collaborative networks, partners may operate at different points along the spectrum. Universities typically focus on early TRLs, level 1 to 4, demonstrating proof-of-concept and validating scientific principles in the lab. Conversely, industry gravitates towards the higher TRLs, particularly levels 7 to 9. At this stage, the emphasis is on refining and demonstrating the technology in an operational environment, ensuring it meets the rigorous demands of industrial applications and is ready for market introduction.

Several authors, including Bonnin Roca & O'Sullivan (2022), Gbadegeshin et al. (2022), Upadhyayula et al. (2018), and Kampers et al. (2021), have leveraged TRLs to map out the necessary technological evolution during the VoD. Notably, Bonnin Roca & O'Sullivan (2022) and Kampers et al. (2021) identified the VoD as spanning TRLs 4 to 7. Upadhyayula et al. (2018) take a more nuanced approach, delineating two distinct phases within the VoD: the 'technology' phase (TRLs 5–6), where the technology is yet to be validated outside lab conditions and for mass production, and the 'commercialisation' phase (TRL 7), where the

technology, despite being demonstrated, faces challenges in commercial feasibility.

Thus, considering the VoD within the context of TRLs 4 to 7, the primary challenge emerges as transitioning the technology from the confines of the laboratory to increasingly realistic and operational environments (see Table 3-1). However, while TRLs provide a useful staging framework, simply progressing linearly through the levels belies the iterative nature of innovation, which often entails navigating back-and-forth based on feedback and refinement. Furthermore, the mechanisms of achieving this transition, as we will explore next, are less documented than the phenomenon itself.

Table 3-1 Environment, stage of development, and fidelity per TRL

TRL	Environment	Stage	Fidelity
1	Laboratory	Research	Basic principles
2			Concept formulation
3			Proof-of-concept
4		Development	Technology validated (lab)
5	Relevant		Technology validated (relevant)
6			Technology demonstrated
7	Operational	Implementation	System prototype
8			Actual system completed
9			Actual system proven

Source. Adapted from European Commission (2014)

3.2.2.2 Existing Guidance Explicit to Crossing the Valley of Death

This section examines key literature offering practical guidance on navigating the VoD in technological development. Research under this nomenclature has started to gain increasing attention in recent years as academics and practitioners explore strategies to overcome this persistent innovation challenge. The aim here is not an exhaustive review of every nuance, but rather to highlight notable studies that directly examine crossing the VoD and who put forth actionable recommendations based on their evidence-based findings.

One central theme is the role of intermediaries and regulatory frameworks in facilitating technology transfer. Islam (2017) proposes a framework combining technology-push and market-pull strategies, using intermediaries to facilitate the commercialisation of new technologies. It emphasises the key role of entities like technology transfer offices in bridging the gap between research and development (R&D) and the market by enabling collaboration, reducing risks and costs, and matching emerging technological capabilities with market demand. This view is complemented by Bonnin Roca & O'Sullivan (2022), who highlight the importance of proactive regulatory engagement by agencies to mitigate investment uncertainties in emerging technologies. Delving deeper into the operational aspects of intermediaries, Takata et al. (2022) explore the role of technology transfer professionals (TTPs) within these entities. They find that for university technology to bridge the VoD, TTPs should leverage existing means to define an initial goal, take an affordable-loss approach to seek stakeholder buy-in, and refine the technology through a trial-and-error process with external partners. The study highlights the necessity for TTPs' persistence, adaptability, and entrepreneurial drive for accomplishing commercialisation. Extending these insights, Son et al. (2022) explore the role of technology holding companies (THCs) in aiding university inventions to cross the VoD. They recommend THCs as dedicated organisations to selectively incubate promising inventions through tailored financing, technical resources, stakeholder links, and commercialisation expertise. They emphasise policies that promote an entrepreneurial culture to aid spin-offs advancement. Taken together, these studies underscore the importance of supportive infrastructure and policies in bridging the gap between technology development and market entry.

Additional insights have been offered on the organisational and innovation processes required to successfully traverse the VoD. Markham et al. (2010) emphasise the importance of distinct roles in bridging the gap between research and product development. They recommend appointing champions to advocate promising ideas, sponsors to provide demonstration resources, and gatekeepers for evaluation criteria. The study highlights the dynamic interplay between these roles, underscoring the need for resources and support for early-stage projects

to succeed towards more formal product development. From their case study on a major cost reduction breakthrough in the automotive industry, Midler (2019) challenges the conventional view of the development phase as rigid and merely preservative of value from earlier creative phases. Instead, he advocates for “fractal innovation” and “innovative development management” during this phase to actively create and capture value. This approach calls for a re-evaluation of traditional design norms, the application of heavyweight project management, and the encouragement of rapid iterative learning within skilled teams. Midler highlights the critical role of strong leadership support in achieving a synergistic blend of original creativity with systematic execution and fostering an environment ripe for agile and in-depth innovation. This perspective suggests that the development phase can be a dynamic and value-adding stage of the innovation process, rather than a static one, enabling projects to bridge the VoD.

Klitsie et al. (2019) recommend taking a design-driven approach to innovation to overcome the VoD in large organisations. They emphasise practices such as early formation of cross-disciplinary teams, rapid prototyping, maintaining user-centred focus, and embracing complexity. Aligning departmental priorities and maintaining a shared vision through effective communication and stakeholder engagement are key to ensuring successful implementation and full realisation of projects. Hansen et al. (2022) propose the adoption of agile principles in industry-academia research projects to overcome the VoD. Key principles include flexibility, collaboration, and iterative learnings. The study emphasises the importance of continual goal adjustment, user interaction, cross-functional teamwork, and empowered project teams. Agile practices foster adaptability and rapid feedback loops across stakeholders, essential for transforming research into successful market innovations. In what has been framed as the first of its kind, Ellwood et al. (2022) propose concurrently pursuing five interconnected and iterative innovation processes to successfully traverse the VoD: refining the narrative for the technology (concept), technical evaluation of lab models (performance), understanding real-world usage (application), comparative value assessment (impact), and integration of innovator actor inputs (strategy). The

integration of insights from technical, user, and business perspectives creates a compelling proposition for further investment.

The research uncovered here begins to unveil various strategies and frameworks to aid technological innovations across the persistent VoD challenge. The focus has largely been on intermediary approaches, such as technology transfer offices (TTOs), particularly in the context of university-industry collaborations. While it is true that TTO's play a central role in the commercialisation of university-developed technologies, there is more to be understood than a simple handover so often depicted in linearly sequenced models. Ellwood et al. (2022) provide an initial processual perspective of some of the more intricate innovation activities, but more research is needed to build a comprehensive understanding of how earlier stage proof-of-concept inventions can improve their technological maturity and increase their chances of successfully crossing the VoD across diverse contexts.

3.3 Context and Methodology

This study adopts a single case study approach to explore the development and application of a novel process framework within an international university-industry collaboration. The collaboration aims to iteratively mature and demonstrate an emerging technology through staged experimentation and evidence-based improvements. The depth and focus of a single case study is particularly suited for such explorations, capturing the nuances and intricacies of contemporary processes in their real-world settings (Dyer & Wilkins, 1991). Moreover, case studies, in general, are powerful tools for diving deep into complex, contemporary phenomena (Eisenhardt, 1989; Yin, 2018). This approach is particularly relevant when exploring how innovation processes, such as the application of a new process framework, can address challenges in the 'technological Valley of Death', where many innovations face hurdles. The insights from this case study can contribute to the broader discourse on strategies to navigate this challenging phase within UICs.

3.3.1 Cranfield Circular Toilet Project

The Cranfield Circular Toilet (CCT) (Figure X) is a non-sewered sanitation technology embedded within a wider initiative known as the Reinvent the Toilet Challenge (RTTC) which is orchestrated by the Bill and Melinda Gates Foundation (Kone, 2023). In 2011, the Foundation's Water, Sanitation, and Hygiene (WSH) program launched the RTTC with the objective of developing sustainable, breakthrough innovative solutions that address the needs of some 3.5 billion people worldwide who lack access to clean and affordable sanitation services (UNICEF, 2023). The initiative most closely aligns with the UN Sustainable Development Goal 6, which focuses on ensuring water and sanitation for all (United Nations, 2023). As such, the CCT represents the forefront of sustainable sanitation innovations.

Figure 3-1 Cranfield Circular Toilet prototypes

The CCT project focuses on a niche area within the challenge known as the Single User Reinvented Toilet (SURT). Here, efforts are concentrated on developing a compact, decentralised system that can be situated within, and process the deposits of, a family household (defined here as five people). This

scope is juxtaposed with the Multi User Reinvented Toilet (MURT) which focuses on larger treatment capabilities situated with public or communal spaces (defined here as 10 to 100 people).

The development of a SURT system is a complex engineering challenge that requires input from interdisciplinary domains (e.g., engineering, design, biological sciences). To date, this challenge remains unmet. The core functionality of the system requires it to separate liquids from solids (frontend) and process them individually (backend), achieving key performance indicators related to effluent water quality and pathogen reduction. A significant portion of these criteria aligns with the ISO 30500 standards (Cid et al., 2022). Beyond this core function, the product must meet multiple other requirements to be considered commercially viable. At the operational level, markers like an operational cost of $0.05 per user, per day are essential (Kone, 2012). The investment cost for the finalised product unit is also constrained, targeting a limit of $500. Achieving these benchmarks would position the technology to enable developing countries to leapfrog traditional sanitation systems, transitioning towards decentralised waste processing.

3.3.2 Activate Partners in the Project During Investigation

The CCT project is an international university-industry collaboration, which, at the time of this research, involves four main actors alongside several different sub-contracted suppliers. Their goals are to develop, optimise, and ultimately bring to market a fully integrated SURT system. Within the WSH program, a specific nomenclature is used to differentiate between the actors involved in new product development and their designated roles, as detailed in Table 3-2.

Table 3-2 Technology development partners and their roles within the project

	Cranfield University	**Company A**	**Company B**	**Company C**
Location	England	USA	Germany & China	China

Active members at the time	10~	10~	9~	14~
Role	Technology Partner (TP)	Engineering Partner (EP)	Commercial Partner (CP)	Commercial Partner (CP)
Role definition	Core technology developer, proof of concept, curation of fundamental IP.	Validate technology, optimise system for robustness.	Adapting technology to commercially viable product, product-market fit, manufacturing and supply chain capabilities.	
Partnership Model	_	Sub-contractor.	Licensee and R&D contract.	Innovative licensee.

3.3.3 CCT Stage of Development

The SURT system, currently spanning TRLs 3–5, encompasses three subsystems: the frontend user interface and the backend solids and liquids processing units. Proof-of-concept demonstrations and validations have been successfully conducted within controlled laboratory settings, where the backend units have met critical ISO 30500 performance benchmarks. Despite this progress, continuous laboratory and preliminary field evaluations, which included a study with 35 participants over nine weeks to assess user interaction with the frontend, indicate that further optimisation is necessary. Challenges remain regarding reliability under variable conditions, steady performance across repeated usage, and interconnectivity between subsystems.

The CCT currently resides in the notorious technological “Valley of Death”, a stage where many successful lab-tested technologies struggle to transition towards commercially viable products. This period is infamously characterised by increased technical uncertainties, financial risks, and the critical need for strategic alignment between development and market requirements. In this valley, the CCT must not only prove its technical viability but also demonstrate its commercial potential.

Successfully navigating this critical stage demands a systematic yet flexible process framework that integrates multi-modal feedback to enhance technology maturity. The CCT has adopted such a framework, with an emphasis on facilitating knowledge exchange and capturing insights from lab, field, and user tests across several different partners. This structured, iterative approach seeks to evolve early-stage prototypes towards a more robust and commercially viable system through continuous refinement and adaptation.

The following sections introduce the ERDE process framework, provide a foundation in relevant literature, and demonstrate its application within the CCT project. Though tailored to the CCT's specific needs, this four-stage framework provides a customisable structure for innovation teams to demonstrate technological improvements through rigorous iterations.

3.4 Introduction to the ERDE Process Framework

The Experimenting, Reviewing, Distributing, and Executing (ERDE) process framework is an iterative and collaborative structure designed to facilitate collaborative technology development in multi-partner projects (Figure 3-1).

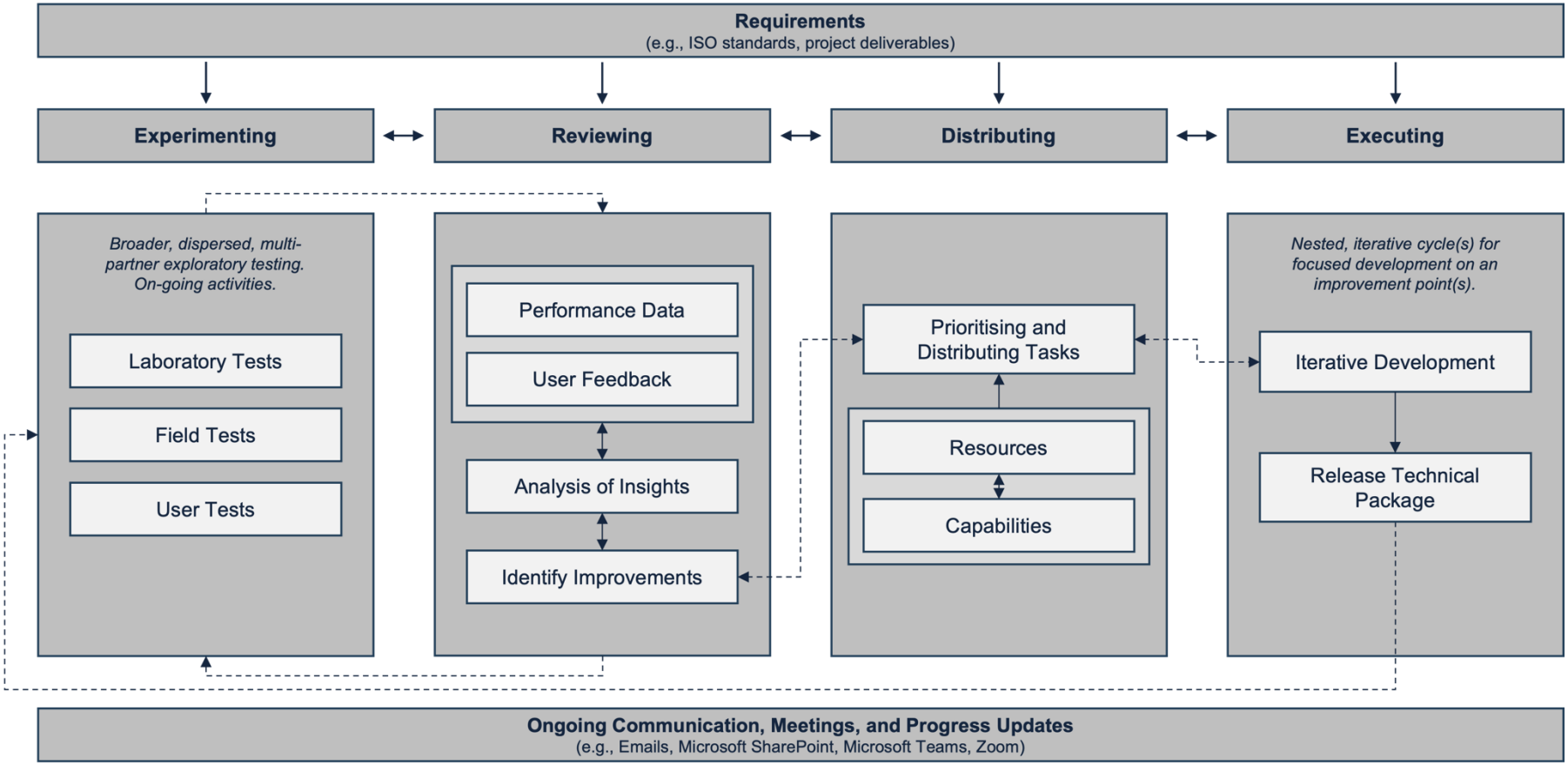

Figure 3-2 ERDE process framework

The ERDE draws inspiration from several established principles, methodologies, and tools. This includes iterative experimentation and prototyping from design thinking (Liedtka, 2015), agile development methods with their emphasis on incremental sprints (Cooper & Sommer, 2016), collaborative knowledge sharing (Cummings, 2004; Olaisen & Revang, 2017), leveraging diverse expertise and capabilities (Batarseh et al., 2018; Lungeanu et al., 2022), risk identification concepts from design-failure mode and effects analysis (Bongiorno, 2001), and RACI matrix principles for responsibility assignment (Smith & Erwin, 2005). The synthesis of these topics allows for the configuration of a framework more adaptable towards dispersed, multi-partner technology development.

The four core stages—Experimenting, Reviewing, Distributing, Executing—emerged from fundamental activities observed in collaborative technology development (Table 3-3). Experimenting involves rigorous testing across varied environments and partner locations to generate data. Reviewing synthesises insights from dispersed findings and identifies improvements. Distributing prioritises and distributes tasks across teams within the collaboration. Executing addresses identified improvements through nested iterative development. Together, these cyclical and interconnected stages facilitate evidence-based improvements to mature technologies and are guided by project requirements.

Table 3-3 Supporting literature for the ERDE stages

Stages	Supporting Literature
Experimenting	At the heart of innovation lies the critical role of experimentation. Experimentation is an adaptive and iterative process driven by exploration and guided by insights (Thomke, 1998). Prototyping and field testing, two common design thinking tools, exemplify this mindset in action. They provide hands-on hypothesis testing approaches that mitigate biases and generate crucial data to stimulate innovative solutions (Liedtka, 2015; Micheli et al., 2018). These activities often reveal what is called ‘unknown unknowns,’ which are unforeseen challenges or requirements that were not initially considered (Jensen et al., 2017). Experimental prototypes also serve as boundary objects that facilitate communication and the coordination of activities between

	and across project teams and stakeholders, enabling collaboration and knowledge exchange (Carlile, 2002; Bogers & Horst, 2014; Lauff et al., 2020).
Reviewing	Results and feedback from experiments relate to either confirming or disconfirming previous hypotheses, optimism, or expectations set forth during experimentation. To move towards improving the maturity of the technology, emphasis should be placed on reframing failures as opportunities for learning (Cannon & Edmondson, 2005). As noted by Thomke (2020), “All experimentation… should generate knowledge. That knowledge comes as much from failure as it does from success” (p. 40). The diverse expertise of individuals across multidisciplinary teams contributes unique tacit insights grounded in their specialised experience (Leonard & Sensiper, 1998; Mascitelli, 2000). These varied perspectives enrich the synthesis of new knowledge formed through streams of experimentation (Cummings, 2004).
Distributing	As technical improvement points are identified, they must be strategically distributed among the available resources within the collaboration. Task allocation leverages the expertise of the distributed teams (and their members) involved (Batarseh et al., 2018). Collaborative planning is crucial, ensuring alignment, consensus, and commitment among the partners (Bstieler & Hemmert, 2010).
Executing	Iterative prototyping stands as a cornerstone for technological development, providing a means to continually refine through structured learning cycles (Mascitelli, 2000; Camburn et al., 2017). Such iterative approaches align with Agile methodologies, where regular sprints, typically two-to-four weeks long, focus on incremental advancements towards the completion of the task (Endres et al., 2022). In physical product development, a sprint’s outcome might not always manifest as a complete prototype. Instead, it could be a design concept, a rapid prototype, or a collection of test results (Cooper & Sommer, 2016; Salvato & Laplume, 2020). These can be conceived as ‘Intermediary Objects of Design’ where prototypes act as “translations and representations of the intermediate states of the final deliverable” (Papadimitriou & Pellegrin, 2007, p. 438).

The ERDE process framework is designed with specific implementation contexts in mind. It is intended for application within established projects, post-initial

planning and partner formation, focusing on iterative technology refinement and maturation during project execution. With this, there must be an existing version of the technology that all partners have access to. The framework is particularly suited for geographically dispersed partners with diverse expertise, utilising digitally-mediated communication tools for coordination. It places strong emphasis on knowledge exchange and collaborative problem-solving, facilitating an environment that both learns by doing and embraces failure. Ultimately, the ERDE aims to provide a practical framework for navigating the challenges associated with bringing inventions towards market readiness. The following sections provide more detail on the interconnected stages within the ERDE framework.

3.4.1 Experimenting Stage

Experiments can occur in controlled lab environments and uncontrolled field settings, with or without users. The choice is dependent on prototype fidelity, work objectives, and desired data. Lab experiments typically focus on feasibility testing of early-stage concepts under controlled conditions by technical team members. Field experiments test technologies closer to their intended real-world application, often enabling user interactions. Lab and field experiments can inform each other through parallel or sequential testing. Within distributed collaborations, concurrent experiments across multiple partners facilitate the generation of multifaceted insights through testing across diverse contexts. Experiments facilitate the production of both quantitative and qualitative data which merge to provide actionable insights, often facilitating further experimentation. This on-going stage focuses on rigorously testing the technology through multiple means to yield insights that inform the next stage.

3.4.2 Reviewing Stage

The reviewing stage takes the multiple streams of experimental results as inputs for analysis and synthesis. Past learnings may also be revisited as new data emerges. The purpose of reviewing is to consolidate various forms of feedback into digestible insights, extrapolating learnings that necessitate improvements to the technology. The continuous nature of the experimenting stage builds

additional perspectives through feedback loops. In distributed teams, email exchange and online video conferencing enables collaborative analysis and the fusing of multidisciplinary perspectives, despite the often asynchronous nature of experimenting within these types of collaborations. To align dispersed partners and stakeholders, synthesised insights are shared via a common online platform. The reviewing stage ultimately produces technological improvement points as outputs that feed into the distributing stage for prioritisation and distribution.

3.4.3 Distributing Stage

Informed by the continual insights from the reviewing stage, the distributing stage is where tasks aimed at technology refinement are prioritised and distributed across teams within the collaboration. Decisions are made based on available resources (e.g., human, financial, technological, and temporal) and the capabilities of the partners (e.g., expertise and innovation capacity). They are also driven by the overarching requirements of the project. Related improvements can be logically grouped where appropriate, forming an interconnected work package. Tasks should be assigned to a ‘responsible person’ to ensure leadership for the task(s). While responsible or leadership roles focus efforts, ongoing communication fosters the utilisation of the collaboration’s collective brainpower. This collaborative process results in an integrated and on-going plan detailing responsibilities. This then forms the foundation for the executing stage.

3.4.4 Executing Stage

In the executing stage, partners and their respective teams enact upon addressing the prioritised improvement points through iterative development. Executing distinguishes itself from the experimenting stage by focusing on ‘nested’ development efforts in response to the identified improvement(s). This is in contrast to the ‘broader’ and more encompassing experimenting stage which is viewed holistically across the partners. Scheduled progress reviews (e.g., biweekly) enable tracking across dispersed efforts. Development is monitored and documented to be shared with all stakeholders. In cases where development may be lagging, or has hit a bottleneck, considerations can be drawn to reassign or reprioritise tasks. Iterative refinements compile into consolidated technical

packages that can be shared among partners for implementation (e.g., 3D print file). Executing transforms insights into purposeful implementations, which then reignites the experimenting stage and facilitates the cycle of development. The cumulative efforts persist on elevating the maturity of the technology in response to new learnings.

3.5 Implementation of the ERDE into the CCT Project

This section demonstrates the application of the ERDE process framework during a crucial development phase between February and July 2022 in the CCT project. The framework provides a structure for identifying, distributing, and addressing improvement points to systematically mature the technology. Three key artefacts supported framework execution and data collection: the Improvement Log and Tracker (ILT), Improvement Observation Card (IOC), and Presentation Metadata Card (PMC).

Cranfield University (TP) and Company A (EP) were active participants in the ERDE. Given the EP's subcontractor relationship, any improvements they developed or contributed towards became the intellectual property of the TP. In contrast, Company B and C (CPs) were considered feedback participants and knowledge recipients. They provided crucial insights from their own testing that helped guide the prioritisation of improvements, while also benefiting from the knowledge outputs and system upgrades enabled through the ERDE activities led by the active participants. This participation model allowed leveraging the strengths of each partner within the constraints of the intellectual property flows.

The following sections demonstrate the participative implementation, showcasing the artefacts in action. Examples illustrate the progression of tasks, role of artefacts in capturing data, and outcomes evidencing technology advancement. This embedded case study provides perspective on the framework in practice.

3.5.1 Improvement Log and Tracker

The Improvement Log and Tracker (ILT) serves as a central repository for capturing, managing, and tracking technological enhancements. The ILT is structured with three primary components: the improvements log, a visual model

of the system, and a traffic light capability scale. These components are usually presented as a cohesive document but for the purpose of readability the visual model and capability scale are shown in Figure 3-2 and the improvements log is depicted in Table 3-4.

	Partners need additional skill support.
	Partners do have the skill, but it will be a challenge to resolve.
	Partners have the skill, and it will be a relatively quick fix.

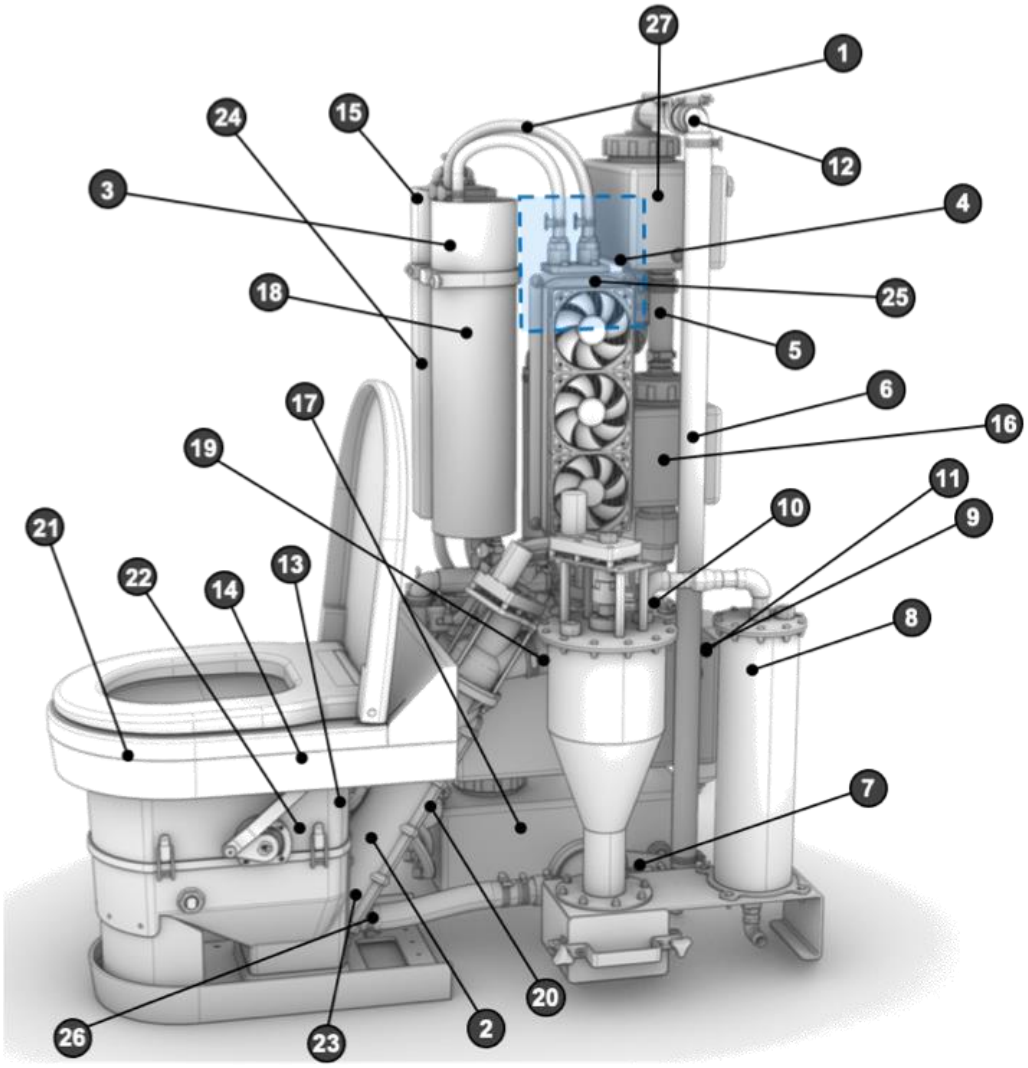

Figure 3-3 Visual model of the SURT system and traffic light capability scale

Table 3-4 Populated improvements log with project data

No	Source	Improvement Identified	Subsystem	Responsible Person	Stage of Develop-ment
1	Lab testing	Air bubbles noticed in MD pipework that could diminish the distillate product rate.	Liquids Processing	Person A [University]	Release
2	Field testing	Screw fracture caused by toilet paper and solids blockage (redesign screw outlet).	Frontend	Person A [Industry]	Release
3	Lab testing	Too much heat transfers through the membrane. Add passive cooling feature – Peltier.	Liquids Processing	Person A [University]	Release
4	Lab testing	Arduino re-sets on powerup.	Control	Person B [University]	Release
5	Lab testing	Heavy gauge hose makes it difficult to access tanks.	Liquids Processing	Person A [University]	Release
6	Lab testing	Main hose linking the diaphragm pump to the two tanks is too large (could be smaller in diameter).	Liquids Processing	Person A [University]	Release
7	Lab testing	Main diaphragm pump could be replaced with a smaller alternative.	Liquids Processing	Person A [University]	Release
8	Field testing	Emissions scrubber pipework to hot tank is higher than brine hot tank inlet. This can create back-flow and odour (one-way valve and u-bend set-up could be applied/used).	Liquids Processing	Person A [Industry]	Release
9	Lab testing	Granular Activated Carbon (GAC) fittings experienced a few leaks at the tank inlet/outlet (better quality fittings required).	Liquids Processing	Person B [Industry]	Release
10	Lab testing	Hot tank could be reduced in size with insulation to retain thermal heat when the hot loops are initiated and the cold tank to be increased in size to act as a heat sink.	Liquids Processing	Person A [University]	Release
11	Lab testing	Granular Activated Carbon (GAC) orientation and fitting is awkward a new	Liquids Processing	Person B [Industry]	Release

		design can be implemented for assembly/disassembly.			
12	Lab testing	Avoid a build-up of solids in pipework by avoiding tight corners and pipework kinks.	Liquids Processing	Person A [University]	Release
13	Lab testing	Hose setup can be simplified for pre-rinse and jet spray.	Frontend	Person C [University]	Release
14	Field testing	Inaccurate volume of water programmed to eject the pre-flush (programme edit required).	Frontend	Person B [University]	Release
15	Lab testing	Opportunity to reduce the number of components in the back end of the toilet – e.g., remove pumps, heat clamps, components, and pipe work where appropriate.	Liquids Processing	Person A [University]	Release
16	Lab testing	Opportunity to reduce tank sizes and location (to improve accessibility).	Liquids Processing	Person A [University]	Release
17	Commercial partner	Odours experienced by the users with discoloration to distillate (recommend faster MD process and brine concentration discharge every 2 days to avoid ammonia/amine build up).	Liquids Processing	Person A [University]	Release
18	Commercial partner	0.6(+/- 0.2) litres of distillate throughput per hour (recommend programming the unit to increase MD cold loop flow rates).	Liquids Processing	Person A [University]	Release
19	Field testing	Compacted solids observed at the screw outlet/torrefaction inlet (redesign torrefaction inlet).	Solids Processing	Person A [Industry]	Release
20	Commercial partner	On one occasion, the mesh behind the screw entangled and worked its way up the screw. Replace with a more robust perforated plate.	Frontend	Person C [University]	Release
21	Field testing	Pan rinse efficiency – add spray nozzles to the inside of the pan and include them in the program.	Frontend	Person C [University]	Release

22	Field testing	Insufficient water-jet spray to rotating bowl in a closed position (programme edit required).	Frontend	Person B [University]	Release
23	Commercial partner	On one occasion the screw broke due to clogging of toilet paper and solids (robustness improvement) – odour noticed when opening the lid (add solids breakdown feature)	Frontend	Person A [Industry]	Release
24	Commercial partner	On the one occasion - two heater band clamps were not achieving desired temperatures (out of 5). Reliability of heating clamps.	Liquids Processing	Person A [University]	Release
25	Lab testing	XBEE (sensor kit) to provide wireless and automatic updates on the condition of the toilet.	Control	Person D [University]	Release
26	Commercial partner	Screw back spray mechanism to periodically clean the screw mesh and avoid blockages over time.	Frontend	Person C [University]	Release
27	Commercial partner	Improve the installation process and robustness of the filter meshes.	Liquids Processing	Person C [University]	Release

The log lists the improvement number, the feedback source, a description of the improvement, the person responsible, the subsystem involved, and the development stage. The visual model offers a graphical representation of the system, allowing users to pinpoint specific areas requiring improvement. This format aids those less technically able, creating a bridge between the table's data and the system's physical components. The traffic light capability scale is employed as a metric to gauge the partners' proficiency in handling each improvement. This scale is known to all collaborative partners and is included across all artefacts as a reference. Green indicates the task is within the immediate skill set, amber suggestions potential challenges yet remains within their capability, and red signifies the necessity for external expertise. As improvement points emerge and are prioritised and distributed, partners discuss which colour is best suited to each task based on these descriptions. This process

typically begins with individual judgments and is then finalised during team meetings. Collectively, the ILT offers a comprehensive and organised view of the improvement trajectory.

The data presented is extracted from project documentation related to a demonstration review for the funders. It showcases the comprehensive iterative development of the system over approximately six months. Throughout this period, a total of 27 captured improvement points were addressed from a larger backlog. These were prioritised for actioning based on current needs and resources. Although marked as “released”, these improvements, once implemented, remain open to further testing and likely subsequent enhancements, facilitated by future cycles of the ERDE process.

Feedback on the system came from a variety of sources: lab testing led with 14 points, followed by 7 from the commercial partner, and then 6 from field testing. Liquids processing was a dominant focus, accumulating 16 improvements, with the frontend next in line with 8. Control and solids processing received lesser attention, accounting for 2 and 1 point(s) respectively.

Delving deeper into the feedback sources, feedback from lab testing primarily targeted liquids processing (11 out of 14), while field testing mostly highlighted frontend issues (4 out of 6), suggesting possible user experience challenges. Meanwhile, the commercial partner’s feedback was split between liquids processing (4) and frontend (3), solidifying these subsystems as primary areas of interest for improvement. Only 1 improvement point touched upon the solids processing subsystem, and, upon closer inspection, this was tied closely to observations related to the frontend during field testing.

The university predominantly took on the responsibility for these enhancements, addressing 21 of the improvement points. In contrast, the industry partner took lead on the remaining 6. Of the 27 improvements, 20 were ranked as green, suggesting clear alignment with existing expertise. The remaining 7 were designated as amber, implying more challenging but attainable undertakings that stretched competencies. This balance of achievable enhancements and

manageable reaches reflects an approach of incremental capacity building alongside regular refinement.

The ILT integrates with both the “Distributing” and the “Executing” stages of the ERDE, offering an overview of all ongoing and upcoming tasks, aiding in informed resource planning. This central hub is crucial for recording improvement points and tracking their subsequent progress. Improvement points collected from the “Reviewing” stage are channelled into the ILT during the “Distributing” phase. Here, discussions are had on their priority and allocation amongst the available resources. Once consensus is achieved and actions initiated, the improvements’ evolutions are tracked across their development stages (details to be elaborated in subsequent sections) during periodic progress updates. This allows for the monitoring of throughput but also aids in identifying potential bottlenecks.

3.5.2 Improvement Observation Card

The Improvement Observation Card (IOC) is a structured artefact designed to systematically capture technological improvement points identified by teams during the “Reviewing” stage (see Figure 3-3).

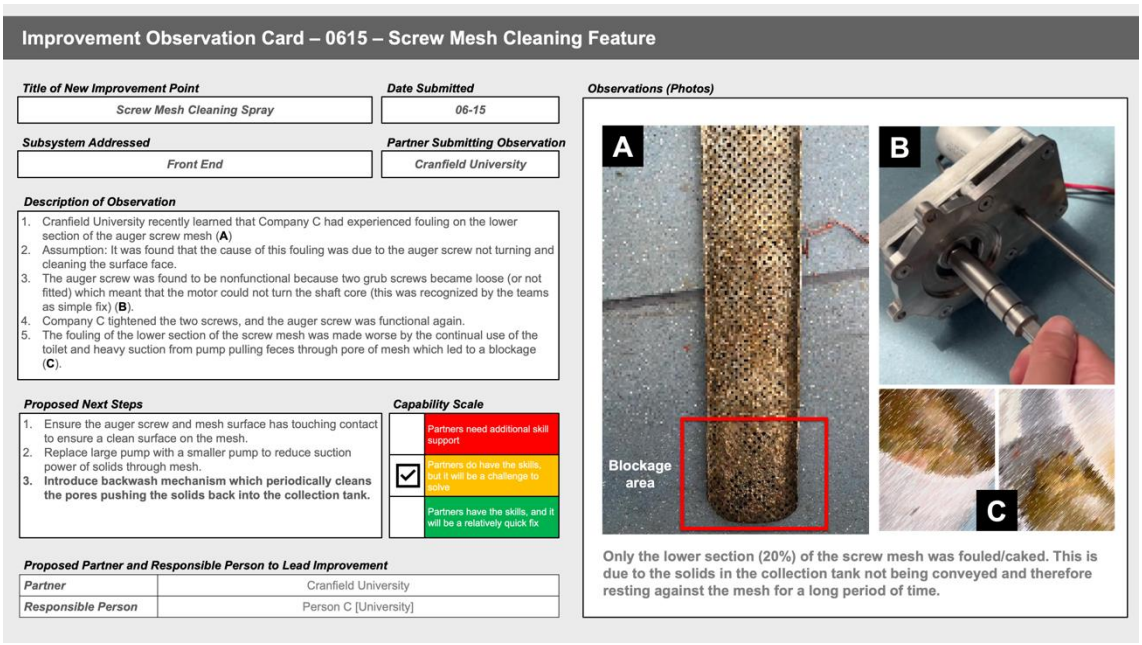

Figure 3-4 Example of the IOC in use

The top section of the card is setup to allow the reader to understand which teams observed the issue, the subsystem it addresses, and when it was submitted. The boxes in the middle-left prompt the author to detail the events that led up to the observation. The bottom-left section then requires the author to submit an initial proposal of the next steps that should be taken to address the challenge along with a suggestion as to who is best suited to become the ‘responsible person’ for that task. The ‘traffic light’ capability scale is used to assess the project partners’ ability to address this particular observation. The section on the right encourages visual representation of what was observed so that the wider project teams can quickly understand the situation. This is particularly important in an internationally collaborative setting.

The example in Figure 3-3 highlights a mechanical failure detected by Company C during system testing. The auger screw malfunctioned, stopping its rotation and preventing solids from exiting the collection tank. This oversight during the experiment led to an overfilled collection chamber and the subsequent fouling of the dewatering mesh, which was exacerbated by the suction from the liquid evacuation pump.

The root cause was identified as two loose grub screws. Once tightened, the motor functioned properly. While the remedy was straightforward, it prompted several preventative measures. As depicted in Figure 3-3, the potential next steps were suggested. The first was not deemed necessary as an improvement point, the second was pre-existing, but the third was captured as a new improvement point. This was incorporated into the list, given an amber ranking on the capability scale, and assigned to Person C from Cranfield University.

This card integrates with the “Reviewing” phase of the ERDE, specifically at the “identifying improvements” step. Within the ERDE process, the card serves as a critical bridge, methodically documenting technological observations and channelling them into the subsequent “Distributing” phase. Its structured format ensures consistent documentation of identified improvements, aiding in the aggregation and analysis of data. As a result, the IOC provides a streamlined tool for recording and recommending identified improvement points that demand

intervention. This new improvement point would then be fed into the ‘Improvement Log and Tracker’ with efforts commencing to address it.

3.5.3 Presentation Metadata Card

The Presentation Metadata Card (PMC) serves as a standardised template for project teams to communicate iterative development progress during virtual meetings (see Figure 3-4).

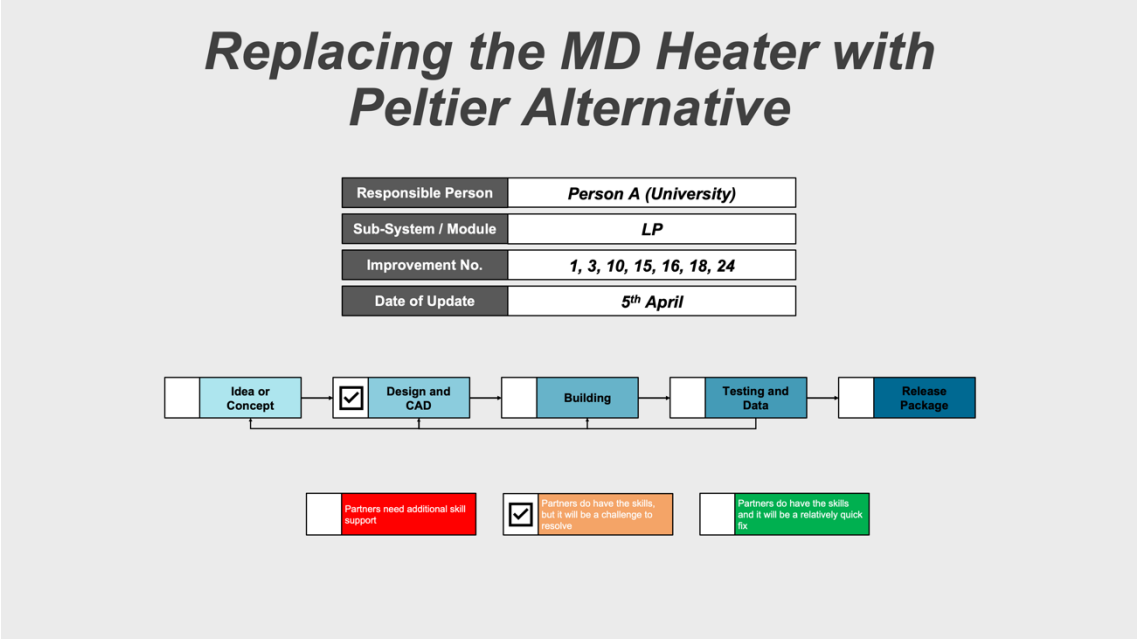

Figure 3-5 Example of the PMC in use

The PMC presents essential metadata related to ongoing improvements. It headlines the overarching investigation or associated improvement point. This is followed by sections detailing the ‘responsible person,’ relevant subsystem, corresponding improvement point number(s), and the date of the latest update. The card then illustrates the current development stage, ranging from initial concept to the release of the technical package. Concluding the overview, a reminder of the capability ranking for the improvement investigation is provided, ensuring attendees are informed of its priority and the challenge at hand.

Two examples of the PMC in use over a series of interval progress updates are presented in Figure 3-5. As the figure shows, two overarching investigations were formed through the technical teams aggregating multiple improvement points –

four and seven respectively (see Table 3-5). One focused on *improving the frontend pan rinse and spray configuration* based on lab and field testing insights. The other involved repl*acing the membrane distillation (MD) heater with a Peltier alternative*, primarily stemming from lab results and commercial partner feedback.

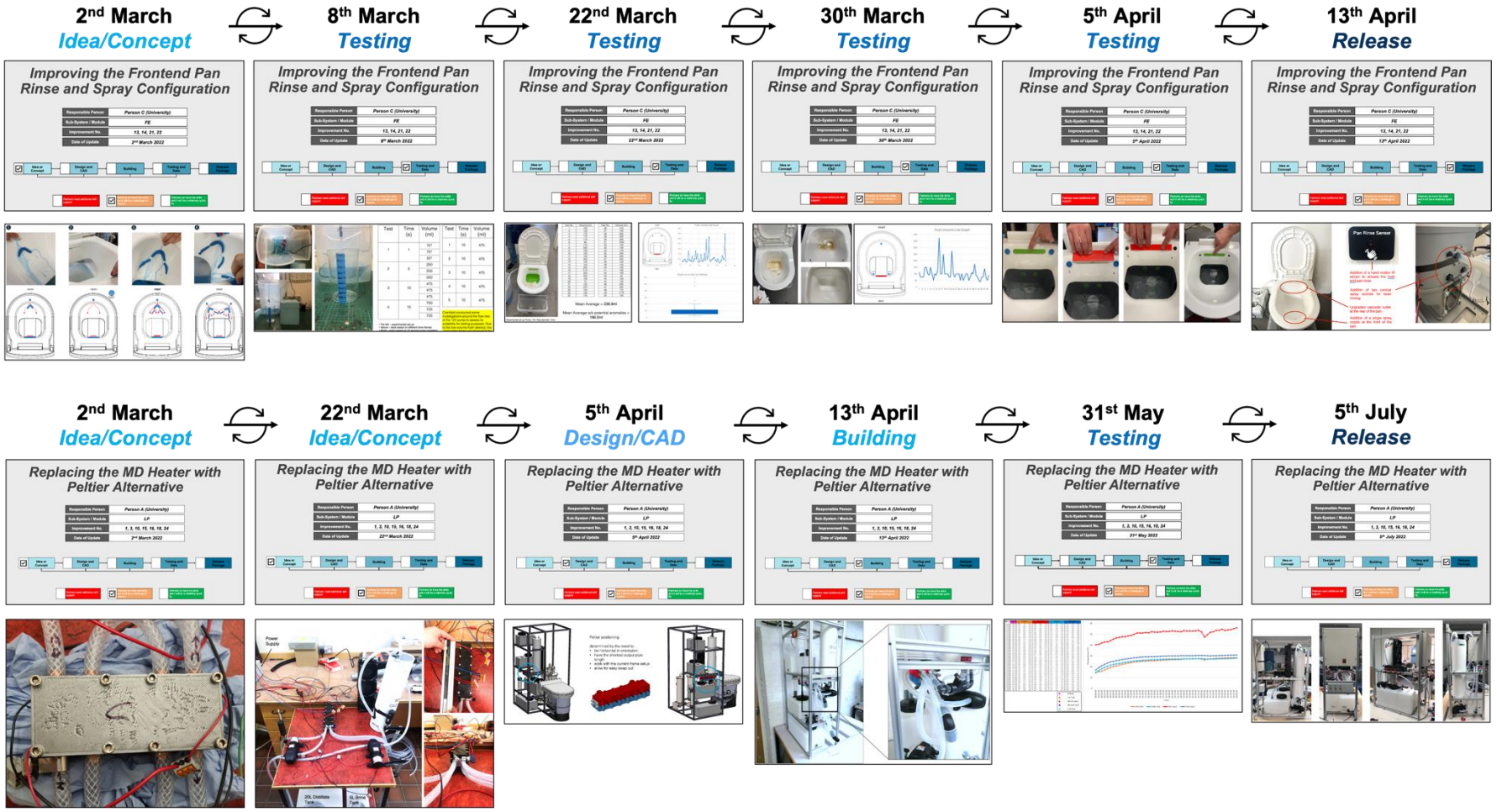

Figure 3-6 Example of the PMC used at interval progress updates

Table 3-5 Examples of aggregated improvement points

Overarching Investigation	Aggregated Improvement Points	Subsystem	First Update (Stage of Development)	Last Update (Stage of Development)	Total Time
Improving the frontend pan rinse and spray configuration	13, 14, 21, 22	Frontend	3rd March (Idea/concept)	13th April (Release)	41 days (1 month, 10 days)
Replacing the MD heater with Peltier alternative	1, 3, 10, 15, 16, 18, 24	Liquids Processing	3rd March (Idea/concept)	5th June (Release)	124 days (4 months, 2 days)

Both investigations marked their first formal update on the second of March. Throughout their trajectories, the responsible person and assigned improvement points remained unchanged. The frontend investigation, detailed in the top row, followed an expedited trajectory, concluding in just 41 days. This swift progress was driven by the application of cutting-edge techniques, notably rapid prototyping and 3D printing. As a result, most of its updates fell within the 'testing' stage, indicative of the recurring iterative cycles characterising this investigation. Alternatively, the liquids processing investigation, depicted in the bottom row, spanned a duration of 124 days. The intricacies of this investigation were underscored by the need for an extensive revamp of the liquids processing subsystem. This comprehensive change brought together seven improvement points, leading to a longer investigation.

The PMC connects to the "Executing" phase of the ERDE process, focusing on communicating progress during iterative development. It facilitates this by tracking the progress of improvements through defined development stages, from initial concept to the release of the technical package. By capturing real-time progression, the card enables synchronisation of dispersed teams through regular updates. It also closes the loop by linking back to the original insights that initiated the improvement task(s). In this way, the PMC provides a streamlined tool for documenting the advancement of enhancements, aiding execution

through incremental innovation. The captured progression via the PMC, evidenced by the content of the following presentation, is then fed back into the overarching ‘Improvement Log and Tracker’.

3.5.4 Linking the Artefacts and the ERDE Together

Figure 3-6 presents a visual showing how the three artefacts link together and with the relevant stages of the ERDE framework.

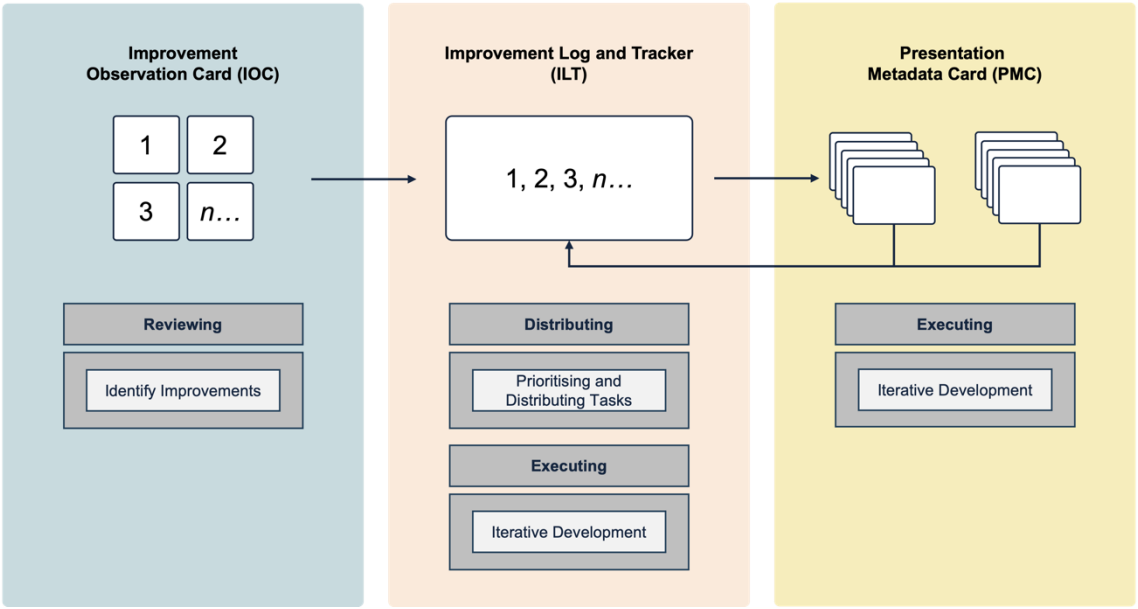

Figure 3-7 Interlinked artefacts facilitating the ERDE stages within the CCT project

The IOC, ILT, and PMC form a system of digital artefacts tailored to support and interconnect with the stages of the ERDE process framework. Each artefact plays a unique role in facilitating the progression through the stages.

The IOC offers a standard template to document insights and improvement needs from the Reviewing phase, based on tests conducted in the Experimenting phase. These feed into the ILT, which serves as a central hub for logging improvements and monitoring their advancement. However, not all captured improvements will become active investigations, with some relegated to a backlog depending on available resources.

The improvements that are prioritised for active investigations undergo development iterations, which are documented using the PMCs. These cards

facilitate regular updates on progress during the Execution phase. The PMCs also provide feedback to the ILT by updating the status of the active investigations.

Together, these tailored artefacts encourage visibility, traceability, and effective workflow throughout the ERDE process through interconnected documentation. In dispersed collaborations, comprehensive documentation is crucial, facilitating clear communication and knowledge sharing among distributed partners, ensuring that all stakeholders remain informed and aligned.

3.6 Discussion

3.6.1 Theoretical Contributions

This chapter introduces a novel process framework, termed the ERDE, designed to facilitate technology maturity through evidence-based iterations within international university-industry collaborations traversing the technology Valley of Death. Through the synthesis of established principles, methods, and tools, the ERDE process framework contributes to the field of collaborative technology development by offering a structured approach to facilitating complex, multi-partner projects. It provides a practical tool for researchers and practitioners to navigate the challenges of geographically dispersed innovation processes, potentially improving efficiency and outcomes in collaborative technology development initiatives.

Demonstrated within the real-world context of the Cranfield Circular Toilet project, the application of the ERDE showcases an iterative, evidence-based approach that builds stakeholder confidence by systematically demonstrating technology maturity and increasing robustness. This approach aligns with authors advocating for more dynamic and flexible approaches to explore avenues in collaborative technology development settings (Liedtka, 2015; Hansen et al., 2022). It also extends research into design-driven approaches to bridging the Valley of Death, moving beyond Klitsie et al. (2019)'s investigation of large firms into the context of geographically dispersed university-industry collaborations.

This study responds to the claims made by Ellwood et al. (2022), who observed a lack of detailed innovation processes for navigating the technology development Valley of Death. Beyond conceptual frameworks, this paper introduces practical, digital artefacts designed to facilitate systematic documentation, traceability, and efficient workflow organisation for dispersed teams working to improve the maturity of emerging technology. The case study offers a granular, applied perspective on how the ERDE process framework and associated tools can enable collaborative teams to reframe failures as learning opportunities, therefore increasing their chances of achieving project goals and securing further funding.

Furthermore, this chapter moves past the typically linearly depicted processes of knowledge and technology transfer, often visualised as a ‘pass the baton’ approach (e.g., Siegel et al., 2004). Instead, it provides a more dynamic and responsive framework in the form of the ERDE that reflects the complexities of real-world technology development and knowledge transfer – beyond, for example, simply licensing fundamental intellectual property. By stepping down a level from drawing conceptual lines between boxes that represent complex and convoluted processes, the ERDE attempts to provide some guidance on these often overlooked processes. Additionally, this study further expands the understanding beyond financial and intermediary aspects, emphasising the importance of strategic process management and stakeholder engagement in navigating the technological Valley of Death.

Finally, and expanding the lens, this chapter demonstrates how universities are active participants in societal, economic, and environmental development through industry collaboration. The case study of the Cranfield Circular Toilet project, part of the broader Reinvent the Toilet Challenge (Kone, 2023), provides a tangible example of how such collaborations can contribute to this (third) mission. Though not a completed project, this university-industry collaboration offers insights into addressing complex societal grand challenges related to global sanitation access, aligning with the goal of academic entrepreneurship to drive real-world societal impact (Fini et al., 2018; Sarpong et al., 2023).

3.6.2 Managerial Implications

The ERDE process framework provides innovation managers with a practical framework to guide collaborative teams through evidence-based refinements of emerging technologies. The proposed iterative structure enables managers to systematically gather feedback, allocate resources, and track development. This continuous refinement based on evidence can lead to more efficient and effective technology maturation, thus increasing chances of further funding or successful development by building confidence in the technology's progression.

The use of documentation and tracking, as seen in the case study, is crucial for maintaining transparency, aligning stakeholders, and ensuring progress in complex, multi-partner projects. Managers should embrace identifying flaws through extensive experimentation as opportunities to improve robustness within project capabilities. This encourages a culture of learning from failure, rather than fearing it (Cannon & Edmonson, 2005). The continuous and real-time documentation facilitated by the ERDE framework enables the generation of more holistic project reports as part of the wider project deliverables. This facilitates comprehensive insights into incremental maturations, setbacks, and lessons learned, as opposed to only static final reporting.

There is a growing interest in identifying emerging technologies and nurturing them across the Valley of Death to address grand challenges. While funding is often foundational, managers also need processes enabling adaptive approaches to endure uncertainties. The ERDE framework proposes an iterative process fitting the ambiguous environment of technology development within collaborative endeavours.

In summary, the ERDE process provides managers a framework to guide evidence-based development, track progress, identifying improvements, and coordinate stakeholders. This adaptive approach can facilitate the enhancement of technology maturation and drive them closer towards addressing societal needs.

3.6.3 Limitations and Future Research

While providing an in-depth demonstration of the ERDE process framework, the single case study methodology limits understanding of its broader applicability and adoption potential across diverse contexts. Examining implementation across multiple cases with different organisational capabilities, aims, resources, and technologies would enrich understanding of the frameworks versatility. Future multi-case research could reveal how the ERDE framework might require adaptation for effectiveness in other collaborative settings and stages of technology development.

The semi-longitudinal nature of this study provides a relatively short insight into the ERDE frameworks implementation. Longitudinal studies tracking the frameworks use across extended time periods could evaluate its long-term impact at different project phases as well as its stickiness.

This research focuses on the framework creators' perspectives. Integrating complementary viewpoints from the various stakeholders engaged in the ERDE process would add depth. Additional qualitative data from industry partners, engineers, and researchers could highlight missed benefits and unexplored limitations of the framework in practice.

Finally, more quantitative measurements around technology maturity and development milestones achieved through the ERDE could enrich understanding of the frameworks effectiveness and practical application.

3.7 Conclusion

This chapter introduced the Experimenting, Reviewing, Distributing, Executing (ERDE) process framework, a novel framework designed to facilitate technology maturity in international university-industry collaborations. Illustrated through the Cranfield Circular Toilet project, the framework demonstrates a systematic approach for iterative technology development, addressing the challenges inherent in the technological Valley of Death. The ERDE framework's practicality lies in its ability to enhance stakeholder confidence and streamline the innovation process through iterative, evidence-based refinements; facilitated here using

three interconnected digital artefacts. Moreover, the framework exemplifies the importance of carefully nurturing emerging innovations; which is a critical step for ensuring that their potential in addressing societal needs is fully realised. This study extends the existing literature by offering a dynamic, responsive approach to technology development, moving beyond linear models of knowledge and technology transfer. Although limited by its focus on a single case, this research emphasises the need to deepen our understanding of, and approaches towards, technological maturation within international university-industry collaborations.

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4 Chapter 4: Gather Around Your Toilet: Synchronisation in an International University-Industry Collaboration

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Abstract

This chapter investigates boundary objects enabling technology and knowledge synchronisation in an international university-industry collaboration focused on the development of an innovative sanitation solution. The research employs an exploratory single case study of the Cranfield Circular Toilet, examining the transition from academic proof-of-concept towards commercial product through a partnership between the UK-based technology partner (TP), US-based engineering partner (EP), and China-based commercial partner (CP). The study focuses specifically on a two-stage synchronisation protocol structured around identical prototype units and standardised protocols tailored to the system's modular architecture. Low-fidelity lab experiments focused on the liquids and solids subsystems respectively. The findings reveal both successes and complications in attaining empirical alignment across sites. While the prototypes and protocols acted as boundary objects to facilitate coordination, divergence also emerged highlighting hidden assumptions and institutional differences between partners. By providing empirical insights into the multifaceted innovation dynamics arising from cross-border knowledge and technology transfer, this research contributes to scholarly understanding of collaborations spanning geographic and institutional boundaries.

Keywords: University-industry collaboration; boundary objects; technology transfer; knowledge transfer; virtual teams; coordination

4.1 Introduction

In today's world, where nearly half of the population is affected by inadequate sanitation (UNICEF, 2023), the urgent need for sustainable solutions cannot be overstated. Addressing this grand challenge necessitates a shift from conventional approaches to breakthrough innovations. University-industry collaborations are crucial in this process, as they bring together the specialised knowledge and skills of academia and industry to develop transformative solutions (Trencher et al., 2014; Ankrah & Al-Tabbaa, 2015; De Silva et al., 2021). Yet, the path from lab to market is not without its hurdles (Ellwood et al., 2022; Battaglia et al., 2023). Prototypes rooted in academic research often do not align with the commercial expectations of industry partners. Bridging this gap requires processes that facilitate shared understanding and synchronisation across organisational boundaries.

Boundary objects have been studied as tools that facilitate collaboration between stakeholders with diverse knowledge and expertise (Carlile, 2002). The concept was first introduced by Star and Griesemer (1989), who described them as artefacts, representations, or concepts that can be interpreted differently by various groups while maintaining enough shared meaning to facilitate collaboration. These objects act as bridges between different 'social worlds' or 'communities of practice,' which allow for the transfer and translation of knowledge across diverse contexts (Wegner, 2000). Their value lies in contexts where collaborating actors have different expertise, priorities, or ways of working, as they provide a shared reference point that can be interpreted from multiple perspectives yet facilitate coordination. Put another way, "[boundary objects] are both plastic enough to adapt to local needs and constraints of the several parties employing them, yet robust enough to maintain a common identity across sites" (Star & Griesemer, 1989, p. 393).

The concept of boundary objects, originating from the field of sociology, has gained significant relevance in innovation management and interorganisational collaboration (Caccamo et al., 2023). As innovation increasingly involves partners external to the focal firm, greater emphasis is placed on sharing knowledge

effectively across organisational boundaries (Bogers et al., 2018). This evolving landscape places emphasis on the importance of understanding how boundary objects facilitate collaboration and knowledge transfer between diverse actors.

The manifestation of boundary objects can happen in many different forms and depends upon the collaboration setting. In product development, various artefacts or representations are generated throughout the different stages and serve different purposes to diverse functions (Pei et al., 2011). Prototypes serve as tangible representations that interdisciplinary stakeholders can engage with and interpret from their unique perspectives (Bogers & Horst, 2014; Heiss, 2020). Of particular note is the 'demonstrator' prototype, which has been emphasised as a platform that can serve multiple purposes at once, from demonstrating scientific principles to visualising potential applications and persuading possible funders or investors (Moultrie, 2015; Bobbe et al., 2023). In virtual engineering environments, 3D building models serve as digital boundary objects that allow geographically dispersed team members to examine designs collaboratively in real-time (Alin et al., 2013). More abstract, and focusing on the front-end of innovation, Zasa et al. (2022) find that visualising one core moment of the customer experience (the 'moment of meaning') can create a boundary object that aligns innovation teams and preserves the key anticipated features as they are pushed through to the next stage of development. Finally, but by no means exhaustive, standardised forms and methods, such as a design failure mode and effect analysis (DFMEA), can exist as boundary objects to facilitate shared formats and language, and serve as transfer mediums for knowledge from different groups (Carlile, 2002).

The proposed effectiveness of boundary objects is based on their "interpretive flexibility" (Star & Griesemer, 1989), which allows disparate groups to observe and interact with them in ways that align with their specific context while maintaining a shared core identity. This flexibility is crucial for bridging diverse perspectives, but it also introduces complexities in international collaborations. In these settings, where interactions are often asynchronous and constrained by diverse organisational cultures (Jimenez et al., 2017), the interpretation and

utilisation of boundary objects can reveal underlying differences in expectations and priorities. Understanding how boundary objects function in these complex environments is crucial for managing collaborative endeavours.

In the context of university-industry collaborations, fundamental differences emerge in terms of perspectives, priorities, time-horizons, and expectations between research-driven academia and market-driven industry (Bruneel et al., 2010; de Wit-de Vries et al., 2019; O'Dwyer et al., 2023). While academia is primarily concerned with advancing science and demonstrating technology feasibility through proof-of-concept prototyping, industry partners are motivated by commercial potential, seeking robust and scalable solutions that can be readily translated into products for real-world markets. These divergent objectives can lead to varied interpretations and utilisations of boundary objects, potentially complicating the collaboration process.

As innovation increasingly transcends national boundaries, understanding the role of boundary objects in international collaborations becomes crucial (Sapsed & Salter, 2004; Caccamo et al., 2023). While the study of global virtual teams is not new to academic discourse (Jarvenpaa & Leidner, 1999; McDonough et al., 2001; Jimenez et al., 2017), the focus when considering boundary objects in such settings has primarily been within the realm of software development (Barrett & Oborn, 2010; Huber et al., 2019). Even when boundary objects are considered in the context of dispersed new (physical) product development, the literature often gravitates towards virtual artefacts such as 3D models and images (Alin et al., 2013; Wlazlak et al., 2019). Furthermore, much of the literature on university-industry collaborations suggests that successful partnerships often occur within close geographic proximity (e.g., Broström, 2010; D'Este & Iammarino, 2010). Rarely do these studies explore the complexities of collaborations that span multiple countries, cultures, and time zones (Govind & Kuttim, 2017; Marques et al., 2023; Suzuki, 2017).

To address this gap, this study investigates the role of physical demonstrator prototypes and digital operating protocols as boundary objects in enhancing the synchronisation of knowledge transfer in an international university-industry

collaboration. Employing a case study approach, the research examines the development process of the Cranfield Circular Toilet, focusing on a collaboration between an academic, engineering, and commercial partner located in the UK, USA, and China respectively. Central to the study is the implementation of a novel synchronisation process, involving the deployment of standardised protocols and identical prototypes to each collaborating entity. The protocols align with the prototype's modular architecture, using lab experiments to validate subsystem operations and facilitate empirical alignment. This research aims to shed light on how boundary objects function in complex, globally distributed innovation collaborations, contributing towards the understanding of effective knowledge transfer and collaboration in international university-industry partnerships.

The remainder of the chapter is structured as follows: Section 4.2 provides an overview of the case study as well as the specifics of the synchronisation protocol. Section 4.3 discusses the empirical results. Section 4.4 summarises the findings, discusses their implications, and addresses the limitations. Section 4.5 concludes the article and addresses its limitations.

4.2 Context and Methodology

This study employs an investigative single case study approach to provide an in-depth analysis of the synchronisation process for the Cranfield Circular Toilet (CCT). As noted by Yin (2018), case studies enable detailed examination of contemporary phenomena within its real-world context (Dyer & Wilkins, 1991). The CCT represents a unique case situated within the broader context of the Bill & Melinda Gates Foundation's Reinvent the Toilet Challenge. This case enables close observation of the knowledge transfer and empirical alignment processes across international partners collaborating to mature and scale up an innovation sanitation technology solution. The case study methodology allows for investigating the complex innovation dynamics arising from the university-industry partnerships between the UK-based Cranfield University, a US-based engineering firm, and a China-based industrial partner. More specifically, this study explores the structuring and transfer effects of standardised prototypes and protocols as boundary objects across the dispersed teams.

4.2.1 Reinvent the Toilet Challenge – Rethinking Sanitation

In 2011, the Bill & Melinda Gates Foundation (BMGF) launched the “Reinvent the Toilet Challenge”, a visionary initiative aiming to redefine sanitation for the future. The goal: to create groundbreaking sanitation solutions that can operate outside the realm of traditional infrastructure; addressing the pressing needs of the 3.5 billion people worldwide who lack access to safely managed sanitation services (UNICEF, 2023). By 2018, numerous innovative technologies emerged from the challenge. However, it was identified that one area of technology required further development: the single-user reinvented toilet (SURT). The SURT reimagines sanitation as a household appliance. It operates independently of sewage infrastructure and treats human waste on-site into harmless by-products. Its modular product architecture encompasses a user interface (frontend) and specialised subsystems for both liquid and solid waste treatment (backend). The target cost is ambitiously priced at $500 per unit with an operational cost of $0.05 per user per day. In sum, the SURT represents a decentralised waste treatment solution which must adhere to rigorous output metrics and cater to the needs of a family household.

4.2.2 Cranfield Circular Toilet – Case Study Context

The CCT is a SURT technology developed out of Cranfield University. It is a “smart” prototype governed by hardware, firmware, and software (Raff et al., 2020). With the BMGF accentuating the need for industrial collaboration, the CCT presents itself as a technology transitioning from university research labs towards intermediary stages of handover processes. This shift necessitates the formation of strategic partnerships to accomplish this goal.

The Foundation’s new product development strategy delineates between three distinct roles: the technology partner (TP), engineering partner (EP), and commercial partner (CP). Cranfield University, as a TP, has the role of technology development lead. Their activities involve the demonstration of proof-of-concept fundamentals, the curation of intellectual property (IP), and the formation of system protocols. The EP’s role is to review the TP’s industrial pilot modules, conduct systematic testing, and propose modifications for robustness. The CP,

on the other hand, is tasked with the commercial ascendancy of the technology. Their responsibilities include licensing the IP, cost optimisation, and spearheading the transition from prototypes to large-scale production. Together, the collective efforts from the TP, EP, and CP are to scale up the technology readiness level (TRL) of the system, conduct lab and field testing, and ensure alignment with rigorous benchmarks (most notably the ISO 30500 standards; Cid et al., 2022).

Although the CCT is funded through the BMGF, it is developed and patented by Cranfield University. It forms part of a larger portfolio of reinvented toilet technologies that have been developed through the Gates Foundation's funding. With motivations to commercialise SURT technologies, the BMGF is engaged in 'engineering' partnerships with prospective industrial entities. 'Engineered' partnerships between academic and industrial entities are those which are facilitated and orchestrated by a third-party as opposed to relationships formed based on perceived complementary needs (Al-Tabbaa & Ankrah, 2019). Cranfield University, as the owner of the technology's IPR, can also facilitate and be receptive to partnerships that are not engineered through the BMGF. Nonetheless, this case study focuses on a synchronisation process between the 'engineered' partnership between Cranfield University (TP), an engineering firm in the USA (EP), and an industrial entity who is located in China (CP).

4.2.3 Overview of the Synchronisation Process

In October 2022, Cranfield University, the TP, hosted a workshop with the EP and CP to present their recent advancements in the SURT system. Attendees observed that the TP had made significant progress, surpassing the previous versions of the technology that had been dispatched to the EP and CP for testing. While this rapid progression was an indication of the project's momentum, it also posed a challenge. The speed of these optimisations meant that the EP and CP found it challenging to keep up, especially when relying solely on digital communication, as well as recognising that their testing results would be non-comparable to the TP's. This divergence underscored the need for a realignment of architecture across the partners located in different parts of the world.

In response, the BMGF commissioned Cranfield University to champion the development of a ‘synchronisation’ protocol. This was conducted in two stages (see Figure 4-1). The first stage involved the creation of three identical SURT units that reflected the latest advancements. By the end of 2022, two of these units were dispatched with one going to the USA (EP) and the other to China (CP). This ensured that all partners would begin the new year with the latest technology in hand.

The second stage was centred on the synchronisation of knowledge. Comprehensive protocols, tailored in alignment with the system’s modular architecture, were crafted with the intent of providing insights into controlling the system. Embedded within these protocols were low-fidelity lab experiments which served dual purposes: a practical experience and providing empirical results to validate the efficacy of the synchronisation process. Here, low fidelity refers to the controlled use of tap water (liquid) and toilet paper (solid) as testing mediums for the SURT. This is contrasted with urine (liquid) and faeces (solid) which are of a higher ‘fidelity’ of testing medium in which the technology is intended to process in an uncontrolled environment.

Q1 of 2023 marked the structured release of three protocols, denoted as A, B, and C. Protocol A was dedicated to the *commissioning* of the system, protocol B concentrated on the *frontend* and *liquids* subsystems, and protocol C focused on the *frontend* and *solids* subsystems (see Figure 4-2). Each protocol came with their respective firmware. The knowledge flowed first from the TP to the EP, who reviewed and conducted the protocols, before they were then clarified and shared with the CP. Each partner conducted the experiments, and the results were then fed back to the TP and cross compared for empirical synchronicity.

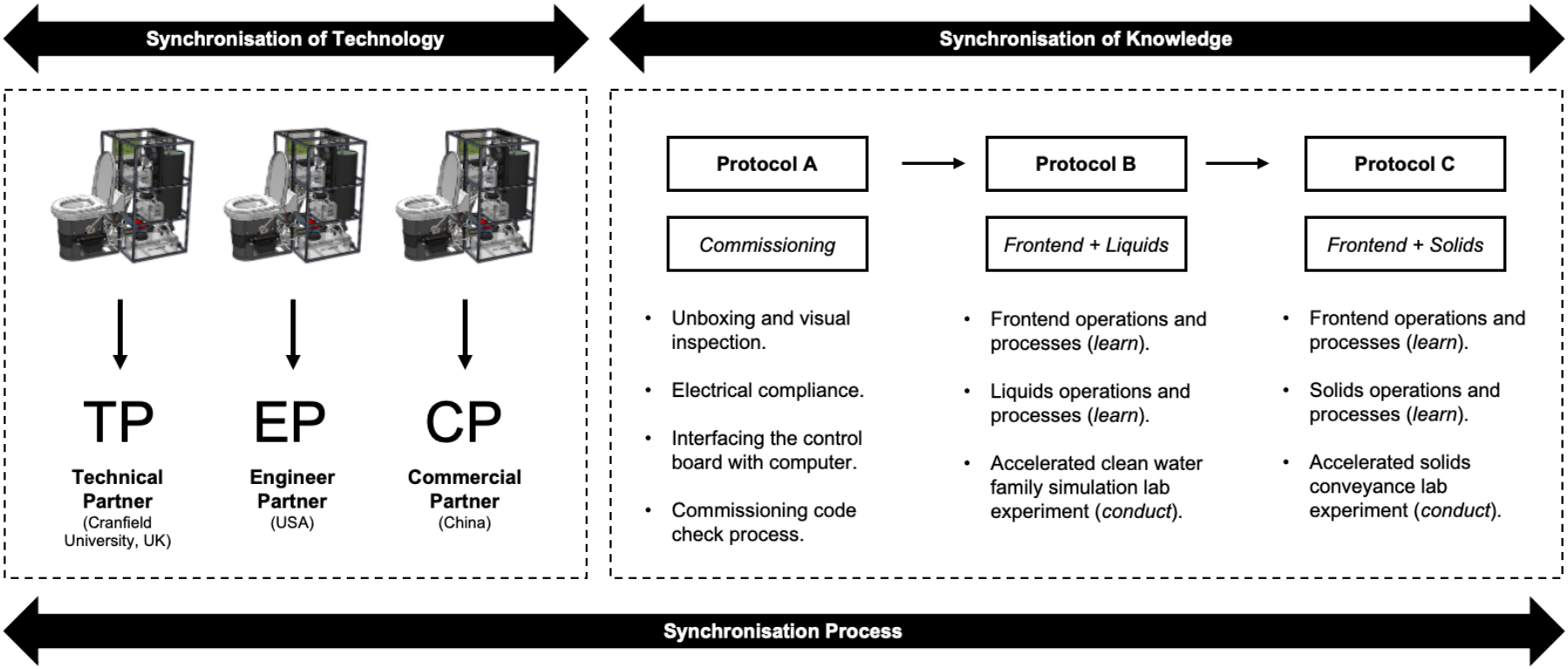


Figure 4-1 Overview of the synchronisation process

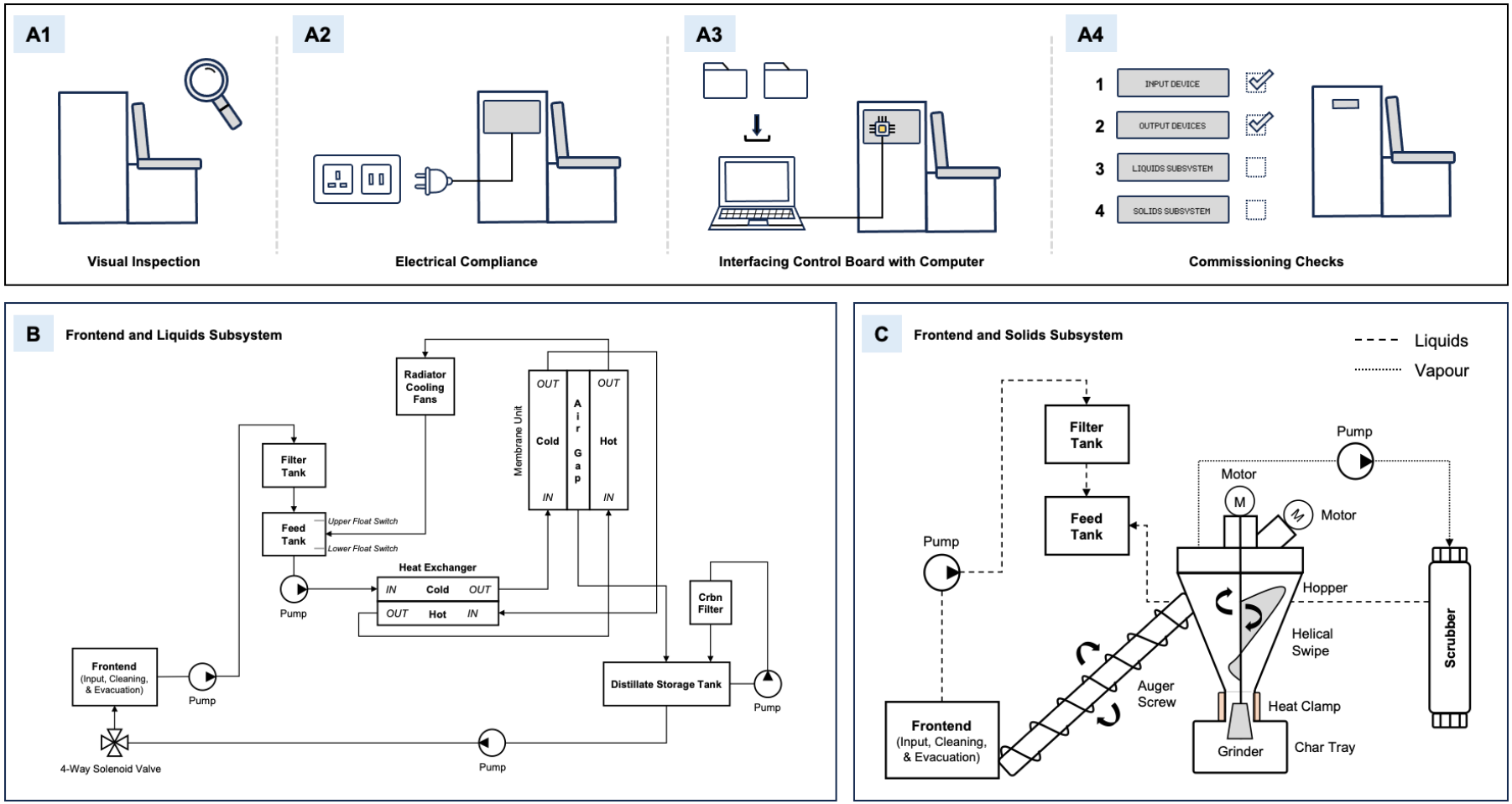


Figure 4-2 Schematics of the protocols and their activities or subsystems

4.2.4 Synchronisation Protocols

4.2.4.1 Protocol A – Commissioning the System

Protocol A involved four key tasks to commission the SURT unit and validate its operational readiness before experimentation, as outlined by protocols provided by the TP. The first task was a visual inspection of both the interior and exterior of the unit, particularly important for the EP and CP receiving shipped units, to check for any physical damage during transport. The second task focused on electrical compliance, requiring partners to adapt the power supply to adhere to local standards and maintain the integrity of all electrical connections. Third was interfacing the control board with programming software through establishing communication between the microcontroller and computer. Finally, commissioning checks were run to validate functionality of all components such as input devices (e.g., pumps), output devices (e.g., thermocouples), and subsystem processes.

No empirical data was collected during the commissioning protocol. The intent was for each partner to rigorously inspect and commission each SURT unit at their respective sites to ensure safety, compliance, and preparedness for subsequent experimental protocols.

4.2.4.2 Protocol B – Frontend and Liquids Subsystem

Protocol B focused on the frontend and liquids operations, and their combined functions. It also involved a practical clean water experiment. This acted as the foundation for empirical synchronisation.

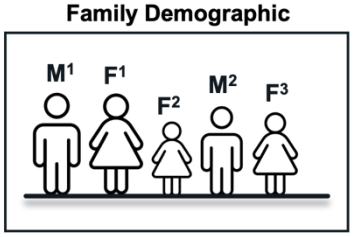
The frontend operations pertained to the toilet cleaning and waste evacuation devices. The liquids operations were outlined regarding their intricate connection to liquid levels, pump behaviours, and temperature fluctuations throughout different phases. Both outlines were also complimented with their respective LCD screen displays during different operational stages.

A low-fidelity laboratory experiment was conducted to test liquids process activation and performance across partners. The experiment followed an

accelerated 6-hour timeline with 23 total ‘drops’ mimicking urine input volumes for a 5-person household. The total input volume per person per day was 1.2 litres based on the upper threshold as detailed in the ISO 30500 standards.

Input drops were staggered across the ‘day’ as per the structured experimental procedure (see Figure 4-3). The timeline attempted to simulate a “morning peak” and “evening peak” as governed by the simulated archetype of the family (e.g., higher usage before and after work or school). The volumes of each drop were dependent on the gender of the user, with females using a higher volume than males. This is because females use toilet paper for cleaning and so the flush button is used to encourage the toilet paper into the rotating bowl via a spray nozzle. This was simulated without the presence of toilet paper but still pressing the button twice.

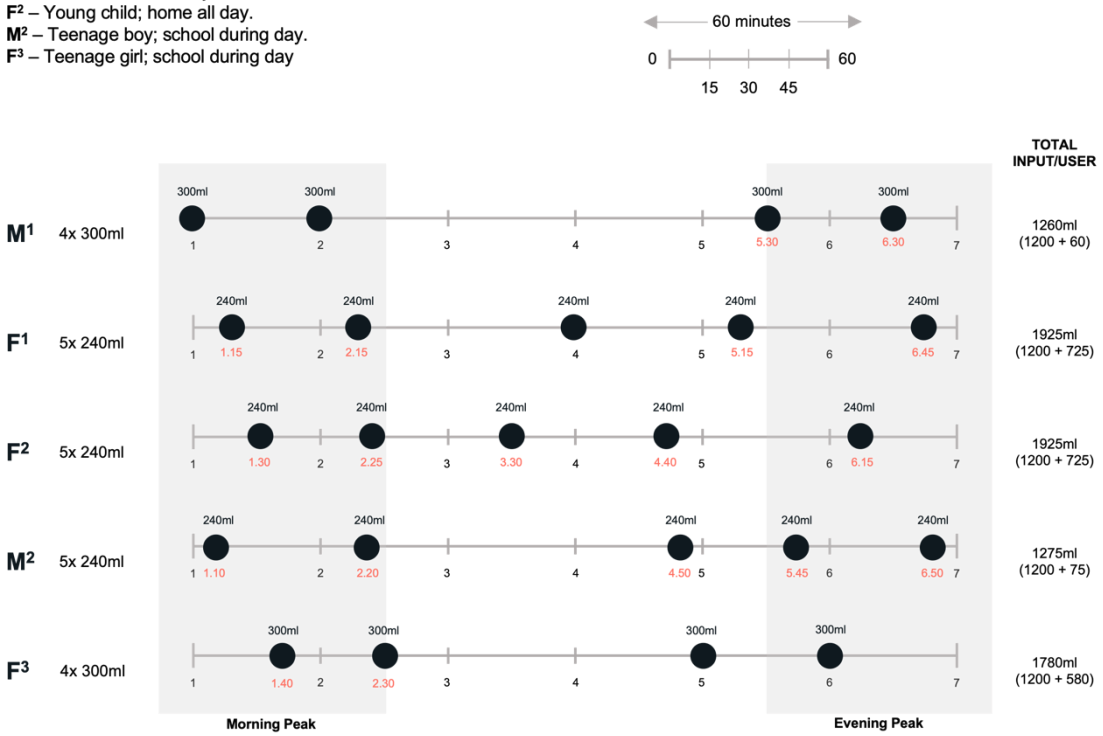
Family Demographic



Simulated Archetypes:
M¹ – Father; work during the day.
F¹ – Mother; home all day.
F² – Young child; home all day.
M² – Teenage boy; school during day.
F³ – Teenage girl; school during day

Total urine input per person per day: 1200ml/user
Urination event volume: 240 or 300ml/user
Pre wetting volume: 15ml~/open
Pan cleaning flush volume (short press): 65ml~/press

Male behavior sequence:
Lift lid → Pre wet (15ml~) → Urination → Close lid.
Female behavior sequence:
Lift lid → Pre wet (15ml~) → Urination → 2x short press (65+65=130ml~) → Close lid.



TIME	1.00	1.10	1.15	1.30	1.40	2.00	2.15	2.20	2.25	2.30	3.30	4.00
VOLUME	300ml	240ml	240ml	240ml	300ml	300ml	240ml	240ml	240ml	300ml	240ml	240ml
PERSON	M¹	M²	F¹	F²	F³	M¹	F¹	M²	F²	F³	F²	F¹
FLUSH	0	0	2	2	2	0	2	0	2	2	2	2

TIME	4.40	4.50	5.00	5.15	5.30	5.45	6.00	6.15	6.30	6.45	6.50
VOLUME	240ml	240ml	300ml	240ml	300ml	240ml	300ml	240ml	300ml	240ml	240ml
PERSON	F²	M²	F³	F¹	M¹	M²	F³	F²	M¹	F¹	M²
FLUSH	2	0	2	2	0	0	2	2	0	2	0

Figure 4-3 Clean water experimental procedure simulating a family of five

Two process activations were expected based on total input volumes. Process activation occurs when the accumulated volume exceeds a threshold as measured by a float switch in the feed tank (see Figure 4-2B). Partners recorded measurements locally including input drop trigger (the drop that triggered the

process), cumulative input volume (how much volume was inputted into the system to trigger the process), process length (the time the process terminated as per the LCD displays timer), and the temperatures of the cold/hot in/out streams at 10-minute intervals.

Temperature patterns were governed by pre-set firmware ranges, particularly for the upper limit of the hot in stream (67-71ºC). Exact values were not expected to match due to uncontrollable variables in each setup. Trend similarities provided measures of empirical alignment.

4.2.4.3 Protocol C – Frontend and Solids Subsystem

Building upon Protocol B, Protocol C adopted a system-level perspective now that all subsystems had been integrated in the firmware. However, despite attaining full system functionality, Protocol C maintained a focus on the frontend and solids subsystem similar to Protocol B's structure. The solids subsystem operations are governed by predefined temperature ranges akin to the liquids subsystem.

To showcase the concurrent functionality of the frontend and solids subsystems, Protocol C incorporated a low-fidelity laboratory experiment aiming to demonstrate front-to-back conveyance of toilet paper throughout the system architecture.

The experimental procedure involved repeated manual input tasks mimicking toilet use (see Figure 4-4). To purposefully accelerate the deposits into the system, each input included 24 sheets of toilet paper. Inputs were conducted back-to-back after each waste evacuation process finished. This was designed to be repeated 27 times for a total of 648 sheets of toilet paper (around 2 toilet paper rolls).

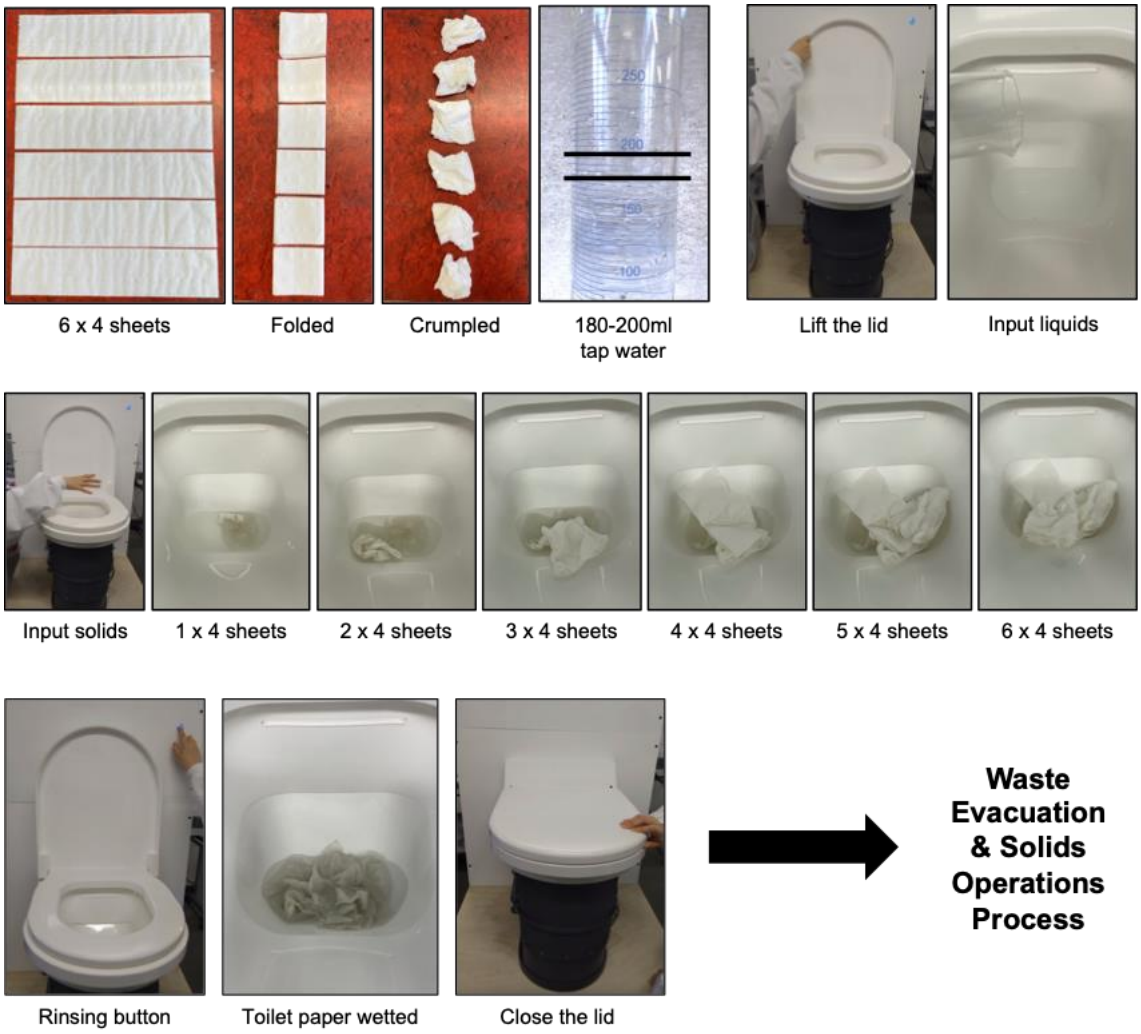


Figure 4-4 Experimental procedure for inputting on solids deposit

To account for the high paper volume, three modifications were made: a hybrid auger screw using soft and hard flights, repositioning the grinder for wider passage, and increasing the motor RPM from 5 to 10 to improve rotational speed and output. These changes also served to demonstrate the adaptability of the system.

Partners documented their observations on paper conveyance through photographs and videos. Visuals captured key aspects like the ‘ragging effect’ of the auger screw to move paper into the screw tube, the hopper filling from the solids transported up the screw, and the output to the char tray after passing through the grinder (see Figure 2C). The goal was to demonstrate efficient front-to-back solids transfer in an accelerated fashion.

4.3 Empirical Findings

4.3.1 Commissioning Results

There were no empirical results from Protocol A. All partners were expected to follow through the steps and conduct the necessary actions to ensure that their unit was compliant for subsequent testing.

4.3.2 Clean Water Experiment Results

An overview of the key metrics from the clean water experiment is presented in Table 4-1.

Table 4-1 Overview of key process metrics from the clean water experiment

	Process 1			**Process 2**		
	TP	**EP**	**CP**	**TP**	**EP**	**CP**
Input drop trigger	11	6	11	22	19	*n/a*
Cumulative input volume (ml)	3955	2100	3955	7910	6825	*n/a*
Process length (mm:ss)	93:45	*np*	267:37	84:25	*np*	*n/a*
Last temperature reading (m)	90	90	260	80	90	*n/a*
Drops during process (*drop numbers*)	4 (*12-15*)	5 (*7-11*)	12 (*12-23*)	1 (*23*)	4 (*20-23*)	*n/a*
Cumulative input volume during process (ml)	1530	1855	4210	255	1340	*n/a*

Note. np = not provided. n/a = no data.

4.3.2.1 Process 1

The TP and CP had consistent start points, initiating the process at the same input drop of 11 which correlated with matched cumulative input volumes (3955 ml). In contrast, the EP started earlier, at drop 6, with a lower cumulative input volume (2100 ml). While the EP did not report process length, the last temperature reading at 90-minutes suggests it was aligned with the TP's duration of 93 min 45 sec rather than the CP's substantially longer time of 267 min 37 sec. Minor differences arose in the number of drops during the process between the

TP (4 drops) and the EP (5 drops), although the additional 355 ml of input for the EP did not impact total processing time. Comparatively, the CP experienced a greater number of drops during the process (12 drops) which correlated with their higher cumulative input volume (4210 ml).

4.3.2.2 Process 2

For process 2, the EP again preceded the TP in initiating the process as shown by the input drop triggers and cumulative input volumes (EP 19, 6825 ml; TP 22, 7910 ml). The CP did not experience a second process. The TP recorded a process length of 84 min 25 sec while the EP's duration based on temperature readings was approximately 10-minutes longer (90 min). This aligns with the higher cumulative input volume for the EP during process 2 (1340 ml) compared to the TP (255 ml).

4.3.2.3 Temperature profiles during the liquids processes

The temperature profiles recorded across both liquids processes are presented in Figure 4-5. This shows the patterns for the cold stream inlet (cold in), cold stream outlet (cold out), hot stream inlet (hot in), and hot stream outlet (hot out) across all three partners.

Figure 4-5 Temperature profiles of liquids streams across process 1 and 2

The temperature profiles across the first process showed close alignment between the TP and the EP over the 90-minute duration. The CP exhibited similar temperature patterns to the TP and EP over the initial 0 to 90 minute phase. However, in the extended 90 to 260 minute period, the CP demonstrated greater fluctuations in temperatures, particularly the hot in exceeding the upper limit of

71ºC multiple times. In summary, the TP and EP achieved strong empirical alignment across the full trial duration. While the CP showed consistent behaviour in the 0 to 90 minute period, more variability emerged in the prolonged 90 to 260 minute phase, indicating divergence from the optimised temperature regulation patterns.

The second process showed continued alignment between the TP and EP over the measured durations. As in the first process, the TP and EP temperature trajectories demonstrated synchronisation and stabilised within the expected ranges throughout the experiment.

4.3.3 Conveyance of Toilet Paper Experimental Results

For Protocol C, the EP did not have a SURT unit available to conduct testing and record results. This was because their system was dispatched after Protocol B for use as a demonstration prototype at an international event. As such, empirical data for Protocol C is only available for the TP and CP.

4.3.3.1 Observations from the TP

The TP provided photos and videos to demonstrate key mechanical aspects of conveying toilet paper (solids) throughout the system. These visuals illustrated the solids conveyance process from input to output (see Figure 4-6).

Figure 4-6A shows the ‘ragging’ and transportation of toilet paper by the auger screw. Figure 4-6B1 presents the hopper beginning to fill as the auger screw conveys solids. Figure 4-6B2 displays the hopper nearing full capacity. Figure 4-6C exhibits the output of the toilet paper after passing through the grinder. The objective was for the CP to observe equivalent solids conveyance behaviours and outcomes when conducting the experiment.

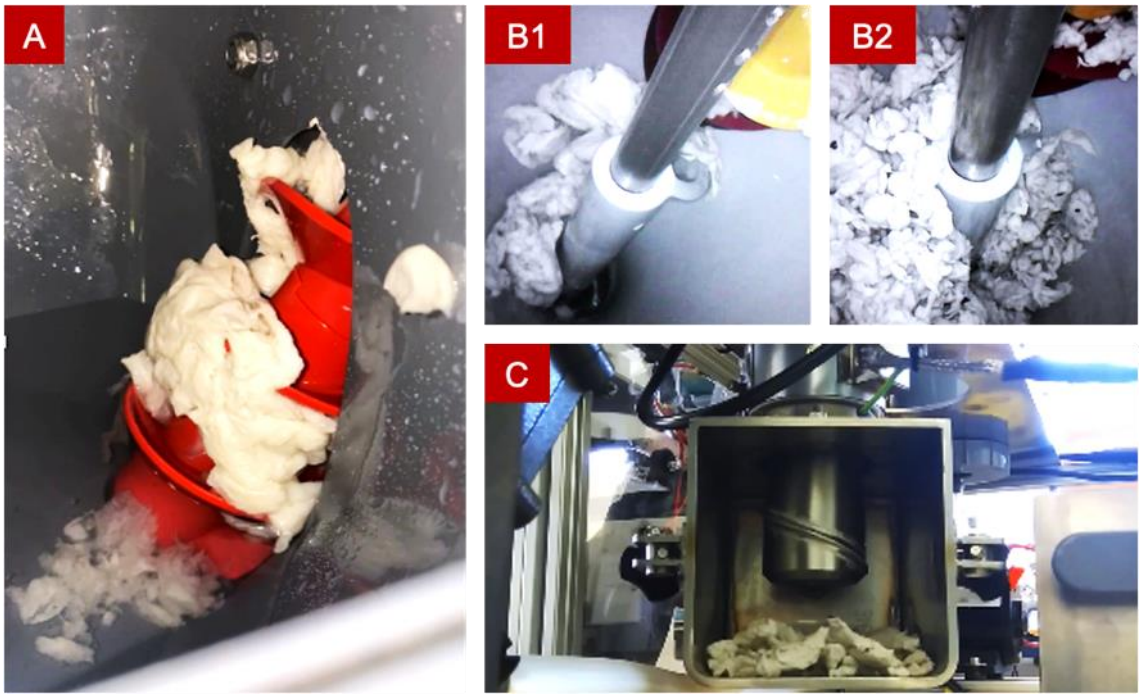


Figure 4-6 TP's visual observation of toilet paper conveyance

4.3.3.2 Observations from the CP

In initial solids conveyance testing prior to implementing the modifications prescribed in Protocol C, the CP experienced inadequate transportation of toilet paper up the auger screw compared to the successful conveyance observed and reported by the TP. This led the TP to formulate the hypothesis that differences in regional toilet paper thickness may impact conveyance performance. Subsequently, the TP provided a simplified, visually focused follow-up protocol reiterating the requirement to use 2-ply toilet paper as specified in Protocol C. After installing the required modifications, the CP demonstrated that their 4-ply toilet paper had to be peeled into 2 sheets to achieve the mandated 2-ply thickness. This evidence supported the TP's hypothesis regarding the influence of toilet paper properties on conveyance functionality. With modifications in place, the CP achieved system conveyance of solids. However, critical observations were shared with the TP (see Figure 4-7).

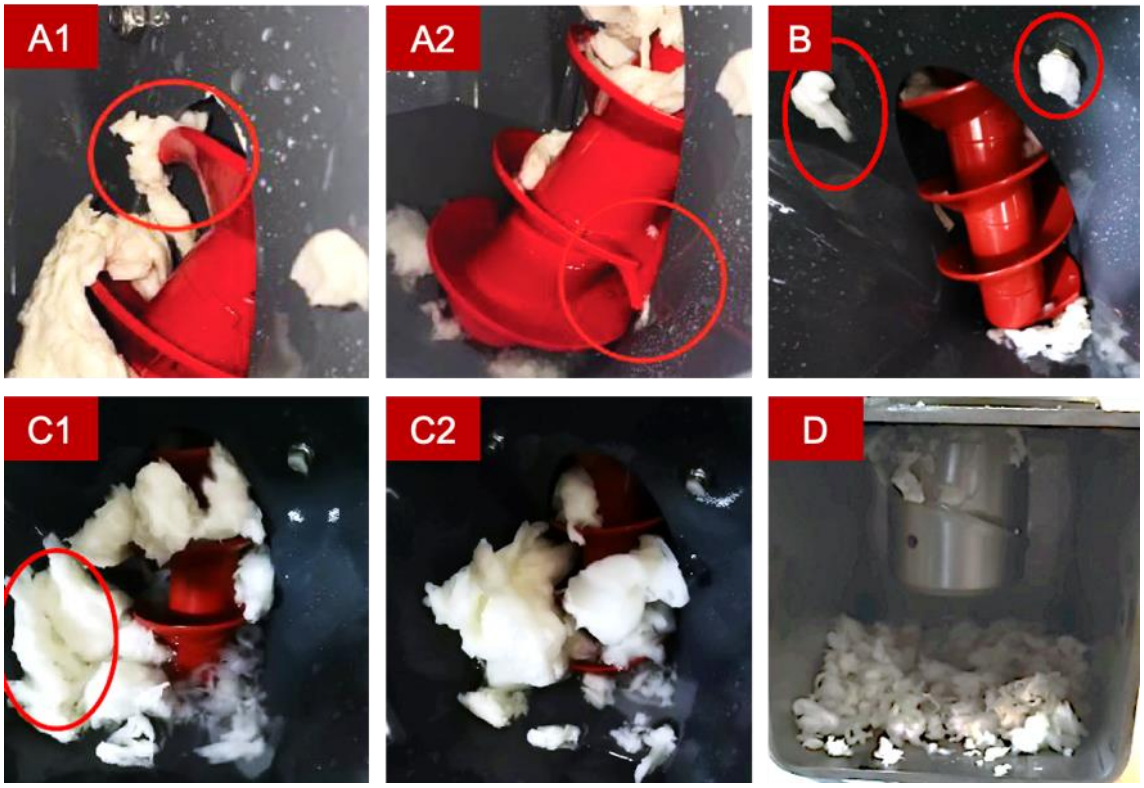


Figure 4-7 CP's visual observations of toilet paper conveyance

Figures 4-7A1 and 4-7A2 illustrate deformation of the auger screw's soft flights when interacting with the toilet paper, which the CP noted could enable paper to become lodged in the resulting gaps. Figure 4-7B exhibits accumulation of paper around the securing bolts on the lower platform during conveyance. Figures 4-7C1 and 4-7C2 demonstrate build-up of solids predominantly on the left side of the rotating auger screw. Figure 4-7D validates successful output of toilet paper into the char tray after conveyance. However, the CP observed retained moisture content which they flagged could potentially impact subsequent human user testing results.

4.4 Discussion

This case study investigated technology and knowledge synchronisation within an international collaboration between university and industry partners. Structured protocols examined system performance across partners located in the UK, USA, and China. Low-fidelity experiments focused on liquids and solids processes. While initial testing revealed alignment between some partners,

inconsistencies also emerged highlighting the need for resolution. The protocols provided insights into system control but also revealed nuances across the distant collaborators striving to mature the technology. The following sections explore the results and findings in further detail.

4.4.1 Summary of Empirical Findings

The most significant finding from the clean water experiment was the divergent results from the CP. Whereas the TP and EP experienced two processes with relative alignment, the CP saw only one prolonged process with unusual temperature patterns. The CP investigated why their results were so different from the TP and EP. It was revealed that the SURT unit contained two 15V power supplies as opposed to one 15V and one 24V as intended. Discrepancies of this nature were expected to be flagged during the electrical inspection step of the commissioning protocol. Nonetheless, it was found that the SURT was not correctly configured. Having found and addressed the root cause, the TP then asked the CP to repeat the clean water experiment.

When receiving the results, the TP realised that the CP had not followed the same experimental procedure as before. Instead, the CP conducted a salt water (brine) experiment, which, although closer to the characteristics of urine, deviated from the synchronisation protocol. They also recorded temperature at 30-minute intervals as opposed to the previous 10-minute intervals. The results showed that the unit was now functioning as intended despite being non-comparative with the results from the TP and EP. It was noted that the CP had included additional measurements in their results which showed more interest towards the performance metrics of the membrane distillation module. The deviation of the CP from the original synchronisation protocol highlights that the market facing partner was more interested in the commercial applicability or robustness of the liquids subsystem than achieving the originally stated objective of attaining comparable results during this phase. Their agenda was closer towards assessing the unit as a product as opposed to a prototype demonstrator.

Despite achieving synchronisation across process measurements, discrepancies were noted between the input drop trigger for both processes between the TP

(11, 22) and EP (6, 19). This indicates differences in experimental starting conditions whereby it is inferred that the EP had a body of liquid within the feed tank before the experiment began. This is observed even when the protocol directly stated that the tank should be drained before starting the experiment. This small nuance alludes to the complications of conducting experiments across dispersed teams within different locations, whereby each partner will interpret the protocols differently or perhaps have their own thoughts as to how it should or could be conducted. Other small differences can relate to ambient temperatures across different countries or human error in measurement reading (i.e., taken at different times). These are uncontrollable beyond outlining what is expected within the given protocol and have to be accounted for when comparing results. These challenges in international collaboration were further complicated by cultural differences impacting experimental outcomes.

The TP produced an additional document for Protocol C to support the Chinese CP. This document was more visually focused to reduce any language barriers that might have been impacting the understanding of the experimental protocol. After providing the additional document, the CP was able to understand the differences in their toilet paper characteristics compared to the TP and quickly adapt to conform with the experimental protocol. In this case, more visually dominant forms of communication improved understanding, suggesting that adapting communication styles to account for cultures differences can be crucial for the success of international collaborations.

The cultural difference observed in the characteristics of the toilet paper were an important learning for the development of the technology. Scenarios like this help to observe where certain biases reigning from the region of the technology developer might be impacting the global acceptance of the technology being developed. This underscores the importance of understanding and addressing the different perspectives and expectations of all partners involved, as further illustrated by the feedback from the CP on the solids conveyance experiment.

Despite achieving solids conveyance after making the required modifications, the outcome to be achieved as per the protocol, the CP took a critical lens when

documenting their observations. In a similar vein to the clean water experiment, the CP took the view of product assessment despite the SURT unit provided being a prototype demonstrator. Their observations of the auger screw deforming during the transportation of toilet paper were factually true, indicating a difference in expectations between the TP and CP regarding the technology's performance at this stage of development. This underscores the importance of aligning expectations and criteria for success among all partners in similar collaborative projects.

Overall, the findings of this study not only shed light on the specific challenges encountered during the CCT project but also have broader implications for the fields of technology handover, international collaboration, and the development of sanitation technology. These broader implications will be explored in greater detail in the following sections.

4.4.2 Theoretical Implications

This research provides an original investigation examining boundary objects in the context of an international university-industry collaboration, extending their application beyond the localised settings commonly found in the literature (e.g., Carlile, 2002; Nicolini et al., 2012). Where research has explored boundary objects in geographically dispersed teams, the focus has largely been confined to the realm of software development (e.g., Barret & Oborn, 2010; Huber et al., 2020). By broadening the scope to encompass product development, this study unveils novel insights into the interplay between physical (prototypes) and digital (standardised protocols) boundary objects in globally dispersed collaborations.

Standardised protocols provided a shared language and framework to coordinate activities. Physical prototypes offered a shared platform for hands-on experimentation, feedback, and refinement between the academic and industrial partners. However, nuances in partner interpretations are revealed that can undermine the functionality of supposedly "shared" boundary objects. This aligns with Star's (2010) assertion that boundary objects are actively constructed through ongoing discussion and do not inherently contain universal meaning. The discrepancies between partners' experimental results and observations highlight

the need for continuous negotiation of meaning, especially when collaborating across geographic, cultural, and temporal divides where typical face-to-face interactions are absent (Sapsed & Salter, 2004). Deviations from the testing protocols further demonstrate the challenge of aligning expectations in asynchronous international partnerships.

Ultimately, by outlining the persistent divergences between university and industry logics despite carefully crafted boundary objects, this research advances theoretical understanding of the inherent limitations these mechanisms face in reconciling deep differences. The findings contribute much-needed empirical evidence on the complexities of synchronising globally distributed university-industry partners, surfacing relevant tensions often obscured in studies of localised collaborations. This yields actionable insights to inform the design and integration of boundary objects within international contexts to proactively mitigate misalignment risks.

4.4.3 Managerial Implications

Misalignment of expectations regarding technology performance emerged as a key complication. This finding highlights the need for project leaders to set clear expectations and success criteria upfront when implementing synchronisation strategies among diverse and dispersed partners. Despite the differences between academic and industry partners being well documented, their differences stand a chance of being flattened, at least momentarily, if they can agree on the expected outcomes of a particular stage of the project; even if the results warrant future resolution.

There is value in partners identifying limitations or areas for improvement in the technology, especially those stemming from cultural differences that may go undetected if only tested in one region. However, it is important that these are flagged for future consideration rather than acted upon during the synchronisation phase dedicated to attaining aligned empirical results across locations. Once baseline performance is verified, a structured review process for proposed iterations can occur. Local insights are valued but should be phase-gated to maintain integrity of the initiative at hand. With this approach, technological

enhancements from localised learning can improve the product without compromising the synchronisation initiative.

This case demonstrates the importance of adapting communication and boundary objects for cross-cultural global innovation projects. The TP's creation of a simplified visual protocol for the Chinese CP improved comprehension where dense textual documentation struggled. This highlights how managers should shape boundary objects to resonate locally, rather than assume a one-size-fits-all approach. Boundary objects should be flexible and adaptable in their design. In cross-cultural contexts specifically, misalignments may signal the need to adapt objects with supplementary representations, media, or interactivity to enhance shared meaning between diverse partners (Wlazlak et al., 2019).

Discrepancies in experimental results due to hardware errors, as encountered in this case, can be avoided if the partner responsible for building and disseminating the technology invests sufficient time upfront to thoroughly test and validate the systems before dispatching the identical units to partner sites. Rather than rushing to distribute units, managers overseeing technology transfer should mandate pilot testing, debugging, and quality assurance testing to confirm all components are functioning properly and meeting the intended expectations. However, upfront testing complicates time management, demanding a balance between technology development and thorough validation. On tight deadlines, careful planning is essential to avoid compromises.

4.4.4 Limitations and Future Research

This research is not without its limitations. The findings are based on a single case, which may limit their broader applicability, pointing to the need for further studies of this nature. While the study delves deep into the dynamics of university-industry collaboration, the underrepresentation of the perspectives of industry partners could limit the comprehensive understanding of the challenges and nuances of such partnerships. There is also a need to understand the benefits and challenges of using the same prototypes in parallel across different geographical locations for synchronisation purposes. Moreover, the research did not address the potential effects of political influence and decision-making during

the synchronisation process. Considering all of the above, future research would benefit from a more inclusive methodology, capturing diverse perspectives and evaluating the broader external factors influencing such collaborative activities.

4.5 Conclusion

Addressing grand challenges, such as inadequate worldwide sanitation, demands innovative solutions that often transcend national boundaries. This study of the Cranfield Circular Toilet, a present collaboration between the UK, USA, and China, provided a microscopic lens into the intricacies of synchronising international university-industry partnerships. Boundary objects, including physical prototypes and digital protocols, were used as mechanisms to facilitate the coordination of knowledge transfer. While boundary objects are designed to bridge knowledge divides, their interpretive flexibility, especially in international innovation contexts, can sometimes be a double-edged sword. This highlighted the enduring challenge of combining academic research and development with commercial expectations; a dance that requires coordination and continuous alignment. Cultural subtleties and different perspectives introduced complexities, emphasising the necessity for clear expectations and adaptable communication strategies when collaborating across borders. Ultimately, this research underscores that while synergising academic and industry priorities across global contexts is an intricate process, with understanding and alignment, such partnerships hold immense potential for pushing forward transformative technologies.

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5 Chapter 5: Discussion – An Integrated Knowledge Transfer Framework

5.1 Introduction to Framework

The integrated knowledge transfer framework, illustrated in Figure 5-1, represents a concise synthesis of the research presented in the previous chapter. It addresses the challenges faced in international university-industry collaborations (UICs) during technology development, particularly within the 'technology' Valley of Death (Ellwood et al., 2022). This refers to the chasm between a technology's validation in a laboratory setting and its validation and demonstration in increasingly relevant environments (i.e., in the real-world) (Upadhyayula et al., 2018), as it attempts to scale towards commercialisation. Inspired by the divergent and convergent phases of the Double Diamond (Design Council, 2015), this framework adapts the concept of iterative learning cycles to the specific contexts of technology development within UICs.

The framework incorporates the widely adopted Technology Readiness Levels (TRLs) (Mankins, 2009), providing a clear progression from fundamental research (TRL 1-3) to pre-production and commercialisation (TRL 7-9). This structure aligns with the typical roles of university and industry partners in the new product development lifecycle (Pujotomo et al., 2023).

At the core of the framework is a diamond shape representing the technology development process (TRL 4-6), focusing explicitly on the 'execution' phase of the project lifecycle (Fernandes & O'Sullivan, 2023). The left side of the diamond, labelled 'Advance', emphasises decentralised iterative experimentation and development across geographically dispersed partners. This phase incorporates insights and learnings from international, multi-partner field testing (FT) and is guided by the ERDE (Experimenting, Reviewing, Distributing, Executing) process framework, which coordinates geographically dispersed development teams.

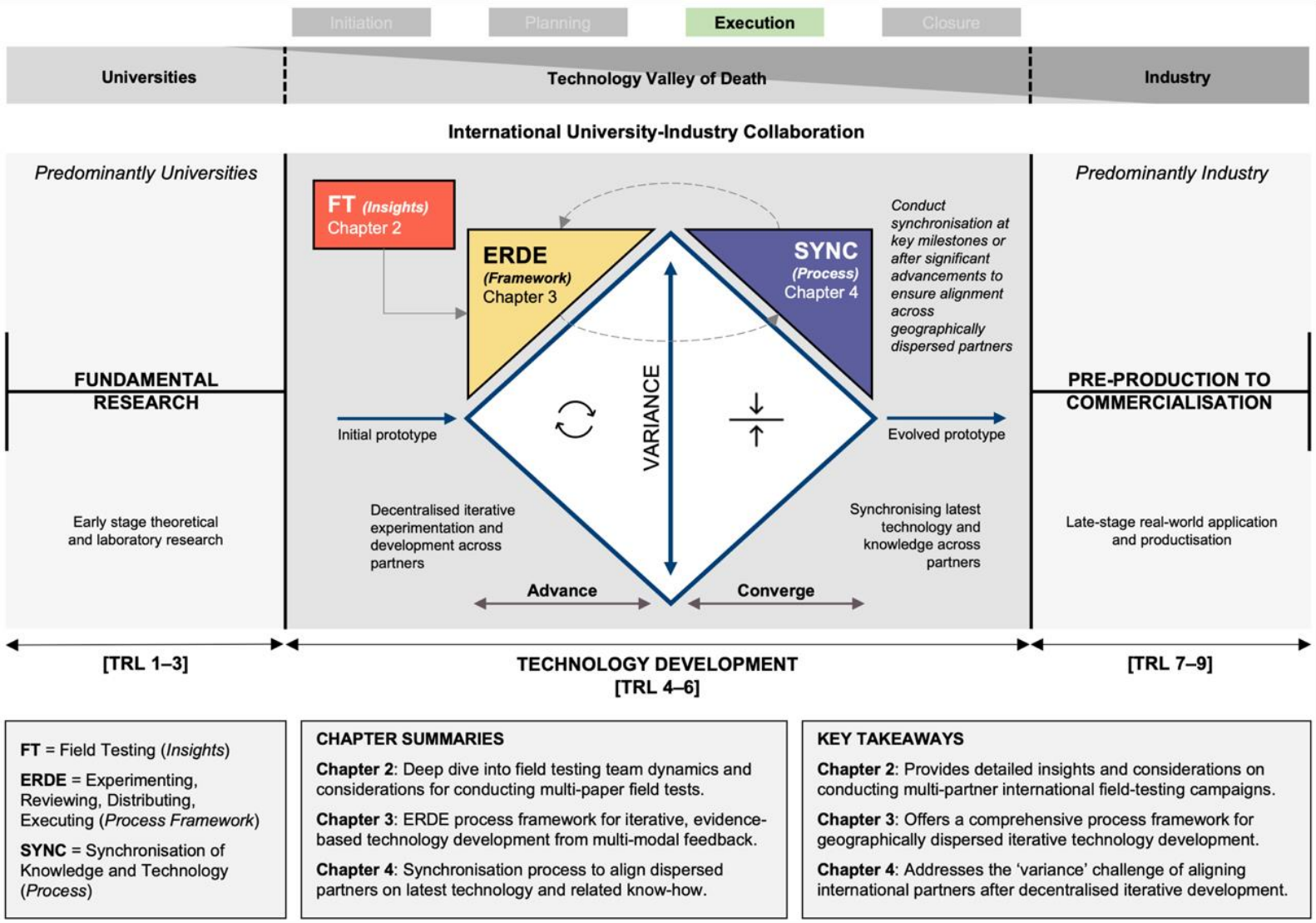

Figure 5-1 Integrated knowledge transfer framework

As development progresses, the framework acknowledges the emergence of variance due to decentralised advancements. The right side of the diamond, labelled ‘Converge’, addresses this through a synchronisation (SYNC) process, aligning partners on the latest technology and knowledge, thereby creating an updated and unified platform. At this stage, the ‘initial prototype’ has now transformed to an ‘evolved prototype’ and inevitably matured. The cyclical arrows that connect the left (advance) and right (converge) sides of the diamond propose that these phases can go through several cycles before finally moving towards sufficient maturation for handover, with the number of cycles depending on factors such as budget, time, and scope.

This integrated framework offers a comprehensive approach to facilitating knowledge transfer in international UICs, providing both academic grounding and practical guidance for navigating the complex landscape of collaborative technology development with commercial handover in mind.

While much of the existing literature on UICs and knowledge transfer focuses on macro-level aspects such as interaction channels, motivations, and barriers, or on quantifiable output metrics like patents and publication (Vick & Robertson, 2018; Acebo et al., 2021), several authors have called for research that delves into the micro-level interactions and processes that occur during these R&D collaborations (Brocke & Lippe, 2015; Albats et al., 2018; Fernandes & O’Sullivan, 2023). Viewing this research through an integrated lens, this framework responds to that call by offering insights into the granular activities and dynamics that unfold during the execution phase of (international) UICs. As such, this research contributes to a deeper understanding of what actually happens at the operational level of UICs.

The following sections breakdown the framework’s components based on the research chapters’ positioning.

5.2 Chapter 2's Positioning and Contribution

Chapter 2, depicted as an orange rectangle, is offset on the left side of the diamond and connects into the yellow triangle representing Chapter 3. The positioning of this paper on the left side is based on its insights into field testing, which constitutes itself as an exploratory activity that examines a technology's application in a relevant environment.

Field testing aims to uncover insights into a technology that can often be missed through lab testing. This is done by introducing the technology into an uncontrolled environment where those interacting with the prototype are unfamiliar with it and do not have any bias towards its performance. The act of field testing allows for development teams to leverage the insights generated to improve the robustness of the technology as it edges towards higher levels of maturity and real-world application.

The specifics of Chapter 2 present a comparative analysis on international, multi-partner field testing campaigns for sanitation prototypes in South Africa and India. Through employing mixed methods, the paper combined quantitative data on team size, structure, and division of labour, with qualitative data focusing on operational insights and considerations. It was through this analysis that the paper aimed to explore the 'behind the scenes' operations during field testing to provide insights and guidance to scholars and practitioners interested in conducting similar activities. This approach was motivated by the observation that several papers on field testing often skipped the operational context in favour of performance data or social acceptance (Sutherland et al., 2021; Welling et al., 2020), and that the closest related study only focused on one operational location and had not covered on-the-ground team dynamics (Sindall et al. 2021).

Key findings showed successful completion of campaigns despite opposing team sizes, with a smaller, more focused team in India contrasted with a larger, more decentralised team in South Africa. Both approaches proved effective for the initial campaigns. Essential feedback for effective international field testing operations were identified: structured collaborative practices, data-driven design decisions, regulatory and ethical compliance, localised technological adaptations,

and local community engagement. These dimensions emerged as key considerations for practitioners and academics when coordinating and executing international field testing campaigns with geographically dispersed teams.

From the shortcomings identified in this paper, beyond its focus on a singular campaign in each country, emerged the need for a collaborative framework that aligns geographically dispersed university-industry teams on their collective mission of technological advancement. This moves past the intricacies of field testing alone, to which Chapter 2 provides detailed insights into, to a more encompassing framework that captures the nuances of a technology's maturation using various activities across internationally dispersed partners. This, in part, instigated the next chapter: Chapter 3.

5.3 Chapter 3's Positioning and Contribution

Chapter 3, visualised as a yellow triangle, is placed on the left side of the diamond, in close alignment with it. Its larger area infers that its offering provides a more central approach to the exploratory half of the knowledge transfer framework. Here, a larger perspective is adopted, beyond field testing alone, to provide structure and guidance for the development activities that occur when advancing the maturity of a technology within internationally dispersed collaborations. This offering is packaged as the Experimenting, Reviewing, Distributing, Executing (ERDE) process framework.

The ERDE is a novel four-stage process framework designed to enhance international university-industry collaborations in advancing lab-based technologies towards real-world application readiness; addressing the technology 'Valley of Death' (Ellwood et al., 2022). It does so through prescribing an iterative, evidence-based refinement approach whereby learnings from experiments conducted by dispersed partners are captured as improvement points, ranked based on the project partners' capabilities and resources to resolve them, distributed to suitable project members based on expertise, and iteratively addressed until an outcome (technical package) is ready to be disseminated. The framework encourages embracing failures as learning

opportunities (Cannon & Edmondson, 2005), promoting a culture of continuous improvement within the constraints of project capabilities and resources.

The framework is positioned within the international collaboration landscape where project stakeholders are geographically dispersed (virtual). This necessitates strong digital communication strategies to bridge the absence of in-person interaction (Duan et al., 2010; Jimenez et al., 2017). The framework's emphasis on documentation and tracking is critical within this realm as it ensures that all stakeholders, regardless of location, are engaged with and informed of progression on learnings and developments. Emphasis on iterative, evidence-based refinements and regular feedback loops allows for alignment amongst these stakeholders, which fosters an informed decision-making process. The transparency of progress also provides funders within evidence-based progression towards the project's goals and requirements.

The application of the ERDE framework was demonstrated in Chapter 3 using the Cranfield Circular Toilet (CCT) as a case study. Three interconnected digital artefacts were created and implemented to facilitate movement across the stages and to capture data and insights within this context. These were named the Improvement Log and Tracker (ILT), Improvement Observation Card (IOC), and Presentation Metadata Card (PMC). In short, the ILT serves as a repository for documenting, overseeing, and maintaining a record of technological progress, the IOC is a structured one-page template designed to capture technical faults as improvements points, and the PMC acts as a standardised template that compliments updates from team members during virtual online meetings. Together, these artefacts interlink to form an evidence-based workflow around the identification and subsequent refinement of technological flaws.

The CCT case study involved four partners whose roles were distinguished between a nomenclature of Technology Partner (TP), Engineer Partner (EP), and Commercial Partner (CP). This role discrepancy not only distinguishes between involvement across the stages of technology development, but also infers intellectual property (IP) flows which must be considered when deploying the ERDE framework within such collaborations.

Chapter 3 distinguished between ‘active participants’ and ‘feedback participants and knowledge recipients’. The former refers to the partners who are actively engaged with the processes within the ERDE framework and are contributing toward its outcomes within an IP agreement. In the case of the CCT, this relates to the TP and EP whereby all improvements resulting from the collaborative work conducted became the IP of the TP due to the EP’s subcontractor relation. The latter refers to the partners, in this case the CPs, who provided feedback as an input to the ERDE, and were recipients of the progression and resulting improvements, but were not actively involved in the process because of potential IP-related conflicts around technology advancements. Despite this discrepancy, it still allowed for knowledge mobility and the identification of multi-modal feedback that needed to be addressed to mature the technology—all while working within the boundaries of the IP flows related to each partners’ role.

Outcomes from the application of the ERDE framework demonstrated the advancement of 27 improvement points downselected from a larger backlog. The framework captured and addressed multi-modal feedback from a variety of sources including lab testing, field testing, user experience, and commercial partner assessment—ultimately leading to advancements across the prototype. Nonetheless, there are important discussion points that must be considered when involved in this type of environment.

Conducting technology development across dispersed international partners presents many challenges. The decentralised nature of advancements leads to asynchronous progress, causing partners to operate out of sync; creating variance. This is despite efforts to remain aligned through digitally mediated knowledge exchange. Several factors can contribute to this.

Misinterpretation of technical files and design documents can occur, which stems from varied levels of technical expertise among partners; highlighting a fundamental challenge in collaborative technology development. This challenge is more noticeable when partners are requires to upgrade the technology instead of simply evaluating a pre-existing model. This is closely tied to the concept of absorptive capacity, which refers to the ability of a partner to understand new

knowledge, integrate it into their existing system, and then apply it practically (Kobarg et al., 2017). For example, with physical prototypes, a partner lacking this capacity might misassemble a new component, which can lead to setbacks, improper testing outcomes, and unjust evaluations. Therefore, partners need to be able to possess technical knowledge and also be capable of interpreting and utilising shared documents and information to facilitate successful knowledge transfer during technology development.

Divergent organisation cultures and work practices between university and industry can present significant challenges, especially when navigating between the contrasting nature of academic exploration and the more application-driven industry (Bruneel et al., 2010). Different innovation cultures further complicate this dynamic relation, as each type of partner may prioritise different aspects of development and innovation. For example, the use of rapid prototyping techniques, which facilitate fast paced iteration, can be a point of contention. Partners who are not familiar or equipped with this approach may struggle to keep pace, leading to discrepancies in development speed and efficiency.

The adoption of digital artefacts across different organisational cultures, and to some extent within, can introduce further complexity to collaborative technology development (Lapointe & Rivard, 2005). New ways of working, such as detailed progress documentation, can be particularly challenging for individuals ingrained in ‘handwork’ and more informal methods of communication. This can lead to a preference for verbal updates or simpler media such as photos and videos; even leaning on others to document progress for them. The varying required workloads of captured improvement points may require the selective use of digital artefacts (e.g., rapidly debugging firmware code vs. rearchitecting an entire subsystem), with smaller tasks benefitting from more flexible and informal documentation methods to effectively track incremental changes within such international collaborations.

International shipping of parts and prototypes introduces several logistical challenges. These include delays, risk of damage during transit, and complexities related to customs regulations. This can cause interruptions in modifications to

the technology and subsequent testing activities. In parallel, language, cultural, and time zone barriers add additional complexities to knowledge transfer across borders (Duan et al., 2010). These barriers cause challenges with regard to a synchronised workflow.

For these reasons, international technology development faces several challenges that can lead to asynchronous integration and potential misalignment among collaborative partners. Nonetheless, diverging paths during decentralised advancements should not always be viewed as detrimental. As the technology advances through different testing activities—such as laboratory, field, and user testing—conducted across various international locations, variations are expected. These differences are valuable as they reveal new insights and hidden aspects of the technology through knowledge exchange, which enable the technology to mature and become adaptive to the cultural and operational conditions to which it is intended to be deployed into. The key goal is to harness these learnings and developments into an upgraded and unified platform (i.e., a ‘design freeze’) that enables convergence between the partners; ensuring that the teams align on their understanding and capabilities around the recent advancements of the technology. This concept was further explored in Chapter 4, which elaborates on an approach towards synchronisation among international technology development partners.

5.4 Chapter 4’s Positioning and Contribution

Chapter 4, envisaged as a purple triangle, is positioned on the right side of the diamond. It serves as a proposed response to the variance that is generated among partners who are concurrently advancing a technology across dispersed locations. Here, an approach towards ‘synchronisation’ is taken whereby efforts align towards converging the latest knowledge and technology after a series of decentralised advancements have occurred—with a particular focus on demonstration. This was conducted through a ‘synchronisation’ process, mediated through the theoretical lens of boundary objects, across international partners.

The synchronisation process prescribed in Chapter 4 focuses on an international collaboration between partners in the UK, USA, and China, who, collectively, are aiming towards the development and eventual commercialisation of a novel sanitation technology solution. This remains the same case study context as Chapter 3 (i.e., the CCT project).

The process was conducted in two stages. The first stage focused on the synchronisation of technology through building three replicas of the advanced system to ensure that each partner had the same version of technology. The second stage focused on the synchronisation of knowledge through creating three protocols that conformed with the modular architecture of the system. Each protocol included detailed knowledge of activities to conduct (e.g., how to commission the system), as well as knowledge on the functionality of the system. This was complimented with low-fidelity laboratory experiments to facilitate empirical measurements of technology performance synchronicity across the partners.

These two stages, technology and knowledge synchronisation, were studied through the lens of boundary objects (Star & Griesemer, 1989; Carlile, 2002). Within the context of technology development, boundary objects are pragmatic tools that contribute towards facilitating collaboration and coordination among diverse partners (e.g., university and industry). Boundary objects are described as being “both plastic enough to adapt to local needs and constraints of the several parties employing them, yet robust enough to maintain a common identity across sites” (Star & Griesemer, 1989, p. 393).

In the context of this international university-industry collaboration, boundary objects help facilitate the alignment of knowledge and expectations between partners from different institutional backgrounds by providing a common technological platform and a shared digital protocol for empirical exploration and mutual understanding. The common technological platform took shape as an advanced system prototype, while the shared digital protocol was formalised as a comprehensive documentation package, providing detailed guidelines for operating the smart system.

Key findings from this study reveal multifaceted insights into the use of physical and digital ‘boundary objects’ when applying them for the purposes of synchronisation across internationally dispersed university-industry technology development partners within a technology handover scenario.

Empirical results across the international partners eventually showed positive signs towards synchronised technology performance. However, along the way, the process encountered issues with divergent results and deviations in experimental protocols. These discrepancies highlight the challenges of coordinating partners dispersed across different borders, time zones, languages, and institutional logics, particularly in the absence of direct, face-to-face interactions (Jimenez et al., 2017). These factors led to misinterpretations and complications in executing experimental procedures. Moreover, in one critical instance, substantial discrepancies in experimental results occurred due to a hardware configuration error in the technology, an issue that could have been addressed in the protocol’s ‘commissioning’ phase. Following the correction of this error, the commercial partner, having been asked to repeat the experiment, diverged from the prescribed protocol to conduct their own assessment. This decision, possibly reflecting a loss of trust, also highlighted the divergent timelines and objectives between the university and industry entities. Although this decision reduced the chance for a precise comparison of results, it still allowed for a general assessment of empirical alignment. This experience emphasises the importance of maintaining alignment throughout all phases of the protocol. It suggests a need for more rigorous signoffs at each phase to ensure all partners remain in sync throughout the process despite their physical and operational distances.

The translation of extensive and comprehensive technical documents across languages presents a significant challenge (Duan et al., 2010). The nuances of these documents can be overlooked or lost depending on the translation service or the expertise of the translators involved. Moreover, translating large technical documents word-for-word can be an overwhelming and time consuming task, often leading to the oversight of crucial subtleties necessary for full

comprehension. To address this issue, adapting communication styles and supplementing them to be more visually focused, such as through the use of photos and videos, has shown to improve comprehension. This was particularly effecting in communicating with the Asian commercial partner regarding the specifics of an experimental protocol. Prior to this, inconsistent results had been observed due to misunderstandings or misalignments in the experimental protocol, specifically related to the cultural variations in toilet paper characteristics like thickness and ply. Therefore, the choice of language and media must be made with careful consideration of the cultural and linguistic backgrounds of the partners involved. Selecting and adapting communication strategies to maximise knowledge transfer is essential to ensure alignment across and between different international partners.

Discrepancies in expectations between the university and industry partners were evident when assessing the prototype technology throughout the synchronisation process. Universities often focus on the 'proof-of-concept' and the iterative nature of technology development, valuing the exploratory process. In contrast, industry partners typically operate on shorter timelines, aiming to quickly exploit and expedite the knowledge and technology. This urgency can reduce their willingness to align with the university's comparatively slower, more exploratory and resilient pace of research and development. It becomes clear that the lessons learned from this dichotomy highlight the need for constant alignment of expectations and outcomes through the synchronisation protocol. Ensuring that partners understand that the technology being evaluated is a prototype with enhanced functionality, rather than a near completed product, is crucial. Such understanding is vital to maintaining alignment on the expected outcomes, acknowledging that the focus is on demonstrating improved technological capability rather than delivering a finalised product.

Chapter 4's investigation into the synchronisation process within a tri-national university-industry collaboration utilised replicated prototypes and shared digital protocols as central tools to facilitate the alignment of technology and knowledge among the partners. Physical boundary objects, such as the replicated prototype

system, acted as tangible points of reference, which were crucial for aligning technological understanding across geographically dispersed teams. In parallel, digital boundary objects, such as the operational protocols, aimed to standardise procedures and knowledge sharing. However, the practical application of these objects encountered a number of challenges. The physical prototype systems required near perfect replication for efficacy, yet subtle differences left undiscovered from the commissioning phase led to divergent experimental results. Conversely, the digital protocols, aimed at providing uniformed procedures, faced misinterpretations due to cultural and linguistic differences, necessitating adaptive communication methods. These complexities in the application of both physical and digital boundary objects across borders highlight the importance of ongoing critical evaluation and adaptation in international collaboration, ensuring that, within the pursuit of alignment, partners acknowledge and respond to the complexities of diverse operational and cultural contexts rather than overlooking them.

The completion of the synchronisation process represents an important point in the framework. At this stage, with access to an evolved prototype that has integrated the decentralised advancements, the collaboration faces a key decision point. Two primary paths forward emerge:

Option A involves feeding back to the left side of the diamond to initiate another round of advancements. This path is appropriate when further development is needed, either because the partners are mid-way through their contract or have agreed to an extension. It also provides an opportunity to address any discrepancies or new challenges identified during the synchronisation process.

Option B concludes the current cycle, treating the evolved prototype as part of the final technology handover. This path may be chosen when the prototype meets the collaboration’s objective or when external factors necessitate conclusion.

The choice between these paths depends upon several factors, including the nature and terms of the collaboration, the allocated timeframe, and an assessment of the benefits achieved. This assessment might consider factors

such as the prototype's readiness for commercialisation, the extent of improvements made, or the potential value of further iterative cycles. By offering this flexibility, the framework acknowledges the dynamic nature of international UICs and encourages adaptive decision-making based on evolving project needs and outcomes.

5.5 Key Considerations and Recommendations

The following section synthesises key practical learnings and recommendations derived from the studies conducted in this thesis. While the findings are rooted in the context of sanitation technology development, many of these recommendations may be applicable to broader UIC scenarios, especially those involving international collaborations and the development and handover of emerging technologies.

5.5.1 Field Testing

Have a core on-site team: Insights from the comparative case study showed diverse team structures and roles across the two countries investigated. It was found that having a core team to spearhead coordination and activities throughout the field testing campaign, with support from specialised peripheral members on specific tasks and decision-making, was an effective approach.

Inclusive and structured collaborative practices: Coordinating field testing campaigns involving multiple geographically dispersed teams proves to be challenging. Challenges can arise around collective decision-making and inclusiveness of partner across the various stages involved in setting-up and executing campaigns. Introducing protocols built around aligning all involved partners in activities related to campaign objectives, prototype commissioning, prototype installation, and data collection can be beneficial in setting expectations. Integrating signoffs into these decisions can provide checkpoints where all stakeholders are satisfied and move forward on the same page. This also reduces downstream delays in testing caused by earlier miscommunication or unverified assumptions, allowing for the effective use of time.

Importance of fast feedback loops in dispersed technology development: Timely data feedback loops are crucially important during international field testing, especially when the technology developer is not co-located at the field testing site. Ensuring that emerging data is fed back to the development teams in a timely fashion allows for iterative refinements to take place while the technology is still in the field. This may materialise as an adjustment to the firmware code or the sending of a 3D print file to install.

Local engagement and technology adaptations: The act of field testing in households directly involves human participants who have volunteered for the cause. This is crucial to consider during the planning and executing of field-testing campaigns (e.g., access to household and extensions to testing periods). All stakeholders need to be aware of this factor. Furthermore, target locations for these technologies may exist in unstable environments when compared to the technology developers setting. This can surface overlooked features within the technology or the execution of the campaign, to which technology developers must accommodate for to ensure continuity in testing. Examples that surfaced from the case studies included the need for robust back-up batteries to withstand local power outages, as well as unstable internet connection impeding real-time data collection and sharing.

5.5.2 ERDE Process Framework

Embracing iterative development to move out of the lab: The ERDE framework emphasises a non-linear, iterative approach to technology development. This approach is key to navigating the uncertainties of the technological Valley of Death, which marks the adaptation of the technology from a laboratory towards increasingly realistic environments. Continuous feedback loops of refinements enables the technology to mature and become more robust against the external factors it is being introduced to.

Systematic documentation and tracking: Introducing digital artefacts as communication and knowledge transfer tools across geographically distributed teams enables for clear communication and documentation of progress. The

Improvement Log and Tracker (ILT), Improvement Observation Card (IOC), and Presentation Metadata Card (PMC) used in the case study allow for structure, tracking, dissemination, and transparency across stakeholders, forming an evidence-based trail of refinements and progress. Approaches of this nature enable dispersed partners to coordinate their development activities and virtually showcase them to wider stakeholders and funders to inform them of their collective efforts.

Integrating multi-modal feedback: Transitioning a technology out of the laboratory towards real-world application requires the harnessing and integration of multi-modal feedback. This includes lab testing, field testing, user feedback, and commercial partner feedback. This is particularly important in scenarios where the technology is being developed for a target region which is notably different from where the technology has originated from. For example, diarrhoea is more common in different regions of the world compared to the 'West' and therefore may not be considered within early technology versions and during user trials in these locations. It is therefore important to encourage adaptability and engagement across all stakeholders to address problems such as these, which will inevitably allow the technology to mature against market and user needs; improving the chances of adoption.

Reframing failures as opportunities to improve: Encouraging the open identification of technological failures and subsequently readdressing them as opportunities to learn and improve is an important factor to integrate into the collaborative culture. Overcoming these challenges through collaborative investigations and experimentation allows the technology to continuously mature towards a market-ready product.

5.5.3 Synchronisation Process

Adapting communication styles across cultures: Divergent results can emerge through misunderstandings within detailed technical documentation and experimental protocols. Adapting communication styles across various partners can improve comprehension. Protocols and documentation for the purposes of

dispersed experimentation should be built around or customised with the receiver in mind – especially across language, cultural, and time zone barriers.

Aligning expectations for successful outcomes: Different expectations of technology performance were revealed in the case study, particularly from the commercial partner, which highlights the inherent interpretive flexibility of boundary objects deployed. It is therefore crucial to emphasise expectations while balancing between divergent partner needs (e.g., university proof-of-concept prototype vs. industry desire for high-fidelity close-to-product). Clearly communicating that advancements have been made to the technology, marking an evolution to the system, but that they do represent the finish is acknowledged as a critical point to make clear. As such, emphasis should be placed on continuous dialogue, feedback loops, and negotiating shared meaning across the partners to provide a common understand of the objects' purpose, functions, as well as limitations.

Validate technology before shipping: The case study demonstrated an example of hardware misalignment leading to divergent results. This emphasises the need for thorough and robust validation of technology replicas before sending them out of the door for the purposes of quality assurance. Projects can move at a fast pace, especially when interfacing with multiple partners and countries, which can lead to unnoticed errors.

Signoffs throughout the protocol: Including signoffs between the transition of each protocol will enable partners to communicate any challenges or frictions faced and ensure synchronisation across each stage of the process more clearly. The hardware error outlined above could have, and arguably should have, been resolved during the 'commissioning' phase of the synchronisation process. However, there was not a platform on which this concern was raised until the experimental protocol results were analysed.

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6 Conclusions

6.1 Summary of Aim Achievement

This section provides a reflective overview of the aim achievement and how it has been conducted through four interlinked objectives.

Aim: To develop and propose a knowledge transfer framework that facilitates international university-industry collaboration in the pursuit of the development and commercial handover of novel sanitation technologies.

Through conducting Objective 1: An immersive exploration of international university-industry collaboration provided practical insights into the field testing of novel sanitation technology. This exploration revealed the complexities and dynamics of real-world settings, underscoring the necessity of adaptable and context-sensitive approaches in technology development and knowledge transfer.

Through conducting Objective 2: The development and application of a conceptual process framework (ERDE) facilitated effective technology development and knowledge exchange. This framework contributed towards the progression from lab-based prototype towards real-world application through the identification and addressal of 27 improvement points captured from various sources.

Through conducting Objective 3: The development of experimental protocols and analysis of performance data enhanced understanding of technology and knowledge synchronisation across international partners. This objective brought to light the critical aspects of aligning various stakeholders' efforts and ensuring that the technology developed is not only innovative but also consistently understood and applied across different contexts. This understanding is vital for the successful commercialisation and scaling of novel technologies.

Through conducting Objective 4: Synthesising and integrating the findings from three distinct studies constructed a cohesive narrative that formed the foundation of the knowledge transfer framework. The synthesis provided a

rounded view of the process, highlighting the interdependencies and the need for a coordinated approach in international university-industry collaborations for developing novel sanitation technology.

The output from the four objectives led to the development of an integrated knowledge transfer framework. This output contributes towards the discourse surrounding the vastly complex landscape of international university-industry knowledge transfer. The framework serves as a blueprint for managing and navigating the complexities involved in developing and handing over novel sanitation technology across international and institutional borders. This research is intended as a thoughtful contribution towards actualising critical sanitation technology for those most in need.

6.2 Contributions to Knowledge

6.2.1 Team Dynamics and Operational Considerations for International Field Testing

Chapter 2 addresses a gap in the existing literature by focusing on the 'behind the scenes' operational dynamics of international, multi-partner field testing campaigns. This is a crucial stage in the product development lifecycle, as field testing stands as an important step for learning about a technology's robustness in uncontrolled and real-life environments. Through a comparative analysis in diverse geographical contexts (India and South Africa), it provides preliminary insights on the effectiveness of diverse team structures on completing field testing campaigns. Specifically, the research revealed that both small, focused teams and larger, decentralised teams can be effective, at least within the initial field testing campaigns. The chapter demonstrates the value of mixed-methods approaches, combining quantitative data on team structures with qualitative insights on operational practices to provide different levels of analysis within the overarching context. It offers transferrable outcomes through insights on on-the-ground team dynamics and programmatic coordination strategies that can inform practices in other fields requiring international, multi-partner collaborations. In particular, scenarios where technology is being developed outside of the target region where it will eventually be deployed, which necessitate international collaborations to fulfil this activity. Within the integrated knowledge transfer framework, this chapter's contributions form the foundational understanding of the complexities within the 'Advance' phase, both on the complication of coordinating international UICs as well as considerations of moving technology from lab to field environments.

6.2.2 Experimenting, Reviewing, Distributing, Executing (ERDE) Process Framework

Chapter 3 develops a new process framework (ERDE) for facilitating decentralised technology development within international UICs, addressing the challenges of the technology 'Valley of Death'. This middle ground of UICs is of critical importance, as acknowledged both within the academic literature and

government policy. It focuses on translating early stage, lab based technology towards higher levels of maturity for its application and deployment within the real world to address socio-economic challenges. Moving beyond macro-level insights on these matters, this study moves to the operational level to provide more granular insights on strategies to navigate this path. It highlights the importance of capturing and transforming insights from multi-modal dispersed feedback (lab testing, field testing, user feedback, commercial partner assessment) into evidence-based improvement points that can be iteratively addressed by project partners; incrementally maturing the technology to improve its chances of being commercialised. The application of the ERDE was demonstrated within an in-depth case study of the Cranfield Circular Toilet. This study introduced three digital artefacts (ILT, IOC, PMC) as tools for enhancing communication and knowledge exchange in geographically dispersed teams, while also facilitating the interconnection of stages across the ERDE. This research provides transferrable outcomes through the ERDE process framework, as well as the exemplar supporting digital artefacts, which can be adapted for use in other forms of international collaborations beyond sanitation technology; for those who are working together apart. Within the integrated knowledge transfer framework, this chapter's contributions act as the driving force for the 'Advance' phase, guiding and coordinating the decentralised, iterative experimentation and development across partners.

6.2.3 Synchronisation Process for Technology Handover

Chapter 4 proposes a novel synchronisation process for aligning technology and knowledge across international partners, addressing the challenge of variance in decentralised development. The study applies the concept of boundary objects in a new context, providing insights into their effectiveness in facilitating knowledge transfer across cultural and institutional boundaries. More specifically, the act of deploying replica prototypes and shared digital protocols across geographically dispersed university-industry partners was investigated. The results highlighted both the intricate challenges and successes of alignment between dispersed U-I partners, focusing on issues such as cultural sensitivities,

misinterpretations, deviations, and necessary adaptations. Under the lens of boundary object theory, this study emphasises the need for consistent (re)alignment and adaptation across cultural and organisational boundaries to facilitate effective synchronisation. For example, when operating across cultural boundaries, adaptations from dense, written documentation to rich, visual media can enhance the transfer and comprehension of technical nuances which may otherwise cascade towards unnecessary tension. Another would be the management of expectations between the university and the industry partner on the maturity of the technology (i.e., prototype not product). Transferrable outcomes can be extracted from this study and applied to other contexts that involve geographically dispersed product development teams that are predominantly digitally mediated. For example, multinational corporations or international research consortia can leverage the insights on using adaptive communication strategies and boundary objects to align understanding across diverse teams. Within the integrated knowledge transfer framework, this chapter's contributions drive the 'Converge' phase by facilitating alignment across partners after prolonged periods of decentralised technological advancements.

6.2.4 Integrated Knowledge Transfer Framework

The integrated knowledge transfer framework (IKTF) presented in Chapter 5 synthesises the three individual research chapters into a comprehensive approach to facilitating knowledge transfer in international UICs. It addresses a gap in the literature by focusing on micro-level interactions and processes during the execution phase of (international) UICs, providing a deeper understanding of operational dynamics. Through integrating multiple stages of technology development (TRL 4-6) into a cohesive framework, it offers a roadmap for both practitioners and (entrepreneurial) academics navigating the technology 'Valley of Death'. Drawing inspiration from the Design Council's emphasis on divergent and convergent phases within the Double Diamond, this framework emphasises a dual-phased approach of 'Advance' and 'Converge'. This offering explicitly addresses the challenges of decentralised development and subsequent

alignment, which are often overlooked in traditional models of UIC, therefore contributing to and extending the discussion of both the theoretical understanding and practical management of knowledge transfer within international UICs.

To illustrate the framework's potential applicability beyond the sanitation technology sector, a few other examples from different fields are considered below.

The IKTF could be particularly relevant in the renewable energy sector, especially for university-industry collaborations developing advanced solar technologies. An example would be a European university-developed, lab-validated solar panel technology being commercialised for rural electrification in Sub-Saharan Africa. This example aligns with the IKTF's focus on international collaborations transitioning technology from lab to real-world application. The framework's 'Advance' phase, incorporating the ERDE process, would guide iterative development crucial for adapting the technology to harsher, more dusty environments – significantly different from European lab conditions. Field testing and multi-modal feedback integration would be essential in this transition and subsequent maturation of the technology towards its intended environment. The 'Converge' phase would ensure synchronisation at key milestones, aligning all partners on the latest technology version and related know-how after decentralised development. For instance, while the industry partner conducts extended small-scale field tests in Africa, the university might be responding to learnings and preparing design improvements for the next iteration. The synchronisation process would ensure all partners are (re)aligned on these recent developments, (re)gain access to the latest version of technology, and share a common understanding of its current capabilities and limitations.

Another sector where the IKTF could provide value is the medical devices sector, particularly for UICs focused on developing diagnostic tools for use in developing countries. For instance, a UK university-developed portable blood analysis device designed for use in remote areas of Southeast Asia aligns well with the frameworks focus of transitioning research-based inventions from the lab to target-region real-world applications. The 'Advance' phase of the IKTF would

guide field testing and iterative development, crucial for adapting the device to local conditions and user needs. The ERDE process could help capture and address feedback on factors like durability, ease of use, and performance in varying environmental conditions (e.g., high humidity). The ‘Converge’ phase would be essential for synchronising the latest decentralised advancements across partners. This could involve aligning understand of recent improvements made to the device’s design or functionality, ensuring all partners regain access to the most up-to-date version of technology and related knowledge.

The IKTF may have limited applicability in sectors such as aerospace, construction, and software development. In aerospace, replicating complex systems like plane or rocket engines at multiple partner sites would be excessively expensive, logistically challenging, and impractical due to the specialised infrastructure required for testing. Similarly, in construction, replicating entire buildings across international collaborations is unfeasible. These sectors often rely on simulation and virtual environments (e.g., digital twins) to reduce costs and facilitate geographically dispersed collaboration. In software engineering, while the principles of field testing, iterative development, and synchronisation are relevant, they operate on much faster timelines compared to physical product development. The intangible nature of code allows for real-time iteration from anywhere in the world, necessitating different collaborative approaches. Although these sectors could benefit from some aspects of the framework, their unique characteristics and existing practices may limit its full implementation.

While the IKTF was developed within the context of sanitation technology, the examples above demonstrate its potential applicability across various sectors involving international UICs, particularly those dealing with physical technology that require adaptations for diverse environments. The framework’s emphasis on iterative development, field testing, and synchronisation addresses common challenges in translating lab-based inventions towards real-world applications across geographical and cultural boundaries. However, as demonstrated above,

its applicability may vary depending on the specific characteristics and existing practices of each sectors.

6.3 Limitations and Future Research

Generalisability of case study research: Case study research allows for in-depth exploration of real-world examples which affords the researcher an opportunity to extract information from and apply knowledge to practical settings. The Reinvent the Toilet Challenge, which forms the contextual setting for this thesis, represents a unique and innovative approach within the global landscape, exemplifying the kind of environment necessary to tackle societal grand challenges effectively. Nonetheless, the primary drawback of this research approach is its generalisability. The focus on individual projects involves subtle nuances and unique characteristics that may not translate well across different contexts, cultures, and technologies. Although this thesis aimed to develop broadly applicable frameworks and strategies, their application and demonstration within unique project settings may disregard the findings' wider applicability; at least until proven otherwise

Future research would benefit from conducting multi-case analysis to investigate different knowledge transfer strategies within the context of the Reinvent the Toilet Challenge to build up a fuller picture of processes and frameworks employed to tackle the intricacies of this global landscape. Furthermore, applying the proposed frameworks and strategies outlined within this thesis across several projects, both within this context as well as across different sectors (e.g., renewable energy), would allow for a more comprehensive assessment of the adaptability and generalisability across different contexts, cultures, and technologies. Highlighting constructive knowledge transfer approaches between universities and industries across international landscapes is crucial given the far-reaching societal impacts that many of these technologies will have on the world.

Inclusion of industry perspective: This research acknowledges the growing importance of university-industry collaborations in addressing complex societal

challenges. These forms of collaboration are intrinsically complex as they cross institutional, and, increasingly, international borders. A noteworthy limitation of this thesis is the lack of industry perspective on the proposed frameworks and strategies implemented. Understanding the double-sided nature of these collaborations is critical for informing best practices within this landscape. Incorporating various industry perspectives would enable the development of more comprehensive strategies that accommodate and compromise towards the needs and logics of both types of partners, ultimately leading towards more sustainable collaborations.

Future research would benefit from incorporating industry perspectives through employing both qualitative methods (e.g., interviews) and quantitative approaches (e.g., surveys). This would provide a more holistic assessment of the proposed frameworks and strategies, leading to more robust and sustainable approaches with comprehensive insights and narratives from both sides of the collaboration.

Opportunities for longitudinal data: The research in this thesis presents semi-longitudinal data and offers insights into the dynamics of collaborative activities that span and progress over several months. However, in contexts where the outcome of the collaboration is ultimately driving towards a societally impactful goal, it is crucially beneficial to collect further data over extended periods of time to provide insightful knowledge on the trajectory and success (or failure) of these collaborations to provide a more comprehensive picture and inform others.

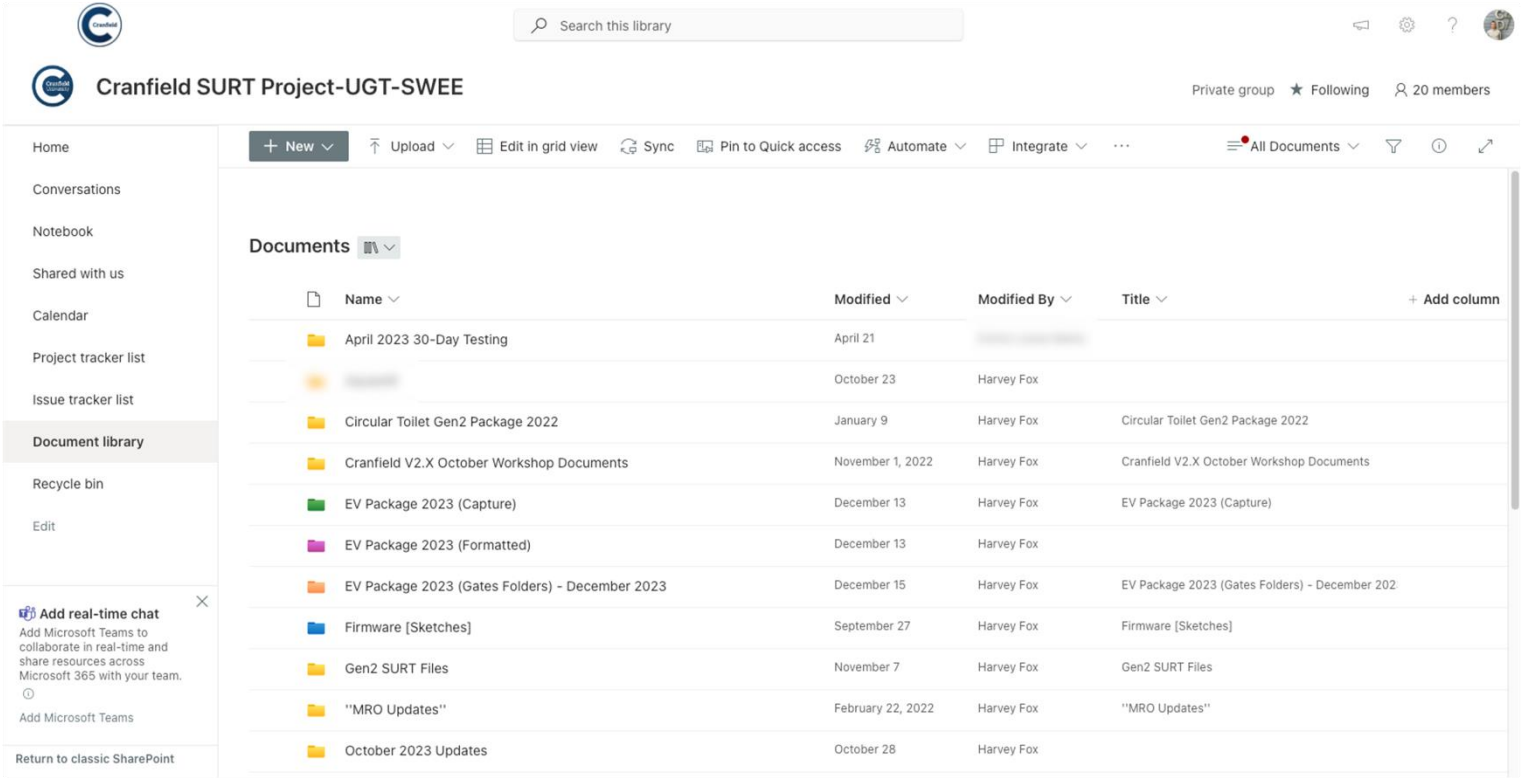
Each paper within this thesis presents opportunities for further study to extend the quality and quantity of data: monitoring additional field testing campaigns to unveil evolving dynamics, exploring longer time periods to assess the evolution and stickiness of processes and tools, and understanding post-synchronisation period impacts. However, the dynamic and ever-changing pace of projects, coupled with the balancing act between research deadlines and real-world challenges, complicates the collection and realisation of longitudinal data.

Appendices

This appendices serve as additional content not suitable for inclusion in the main thesis but rather as supplementary information and demonstration.

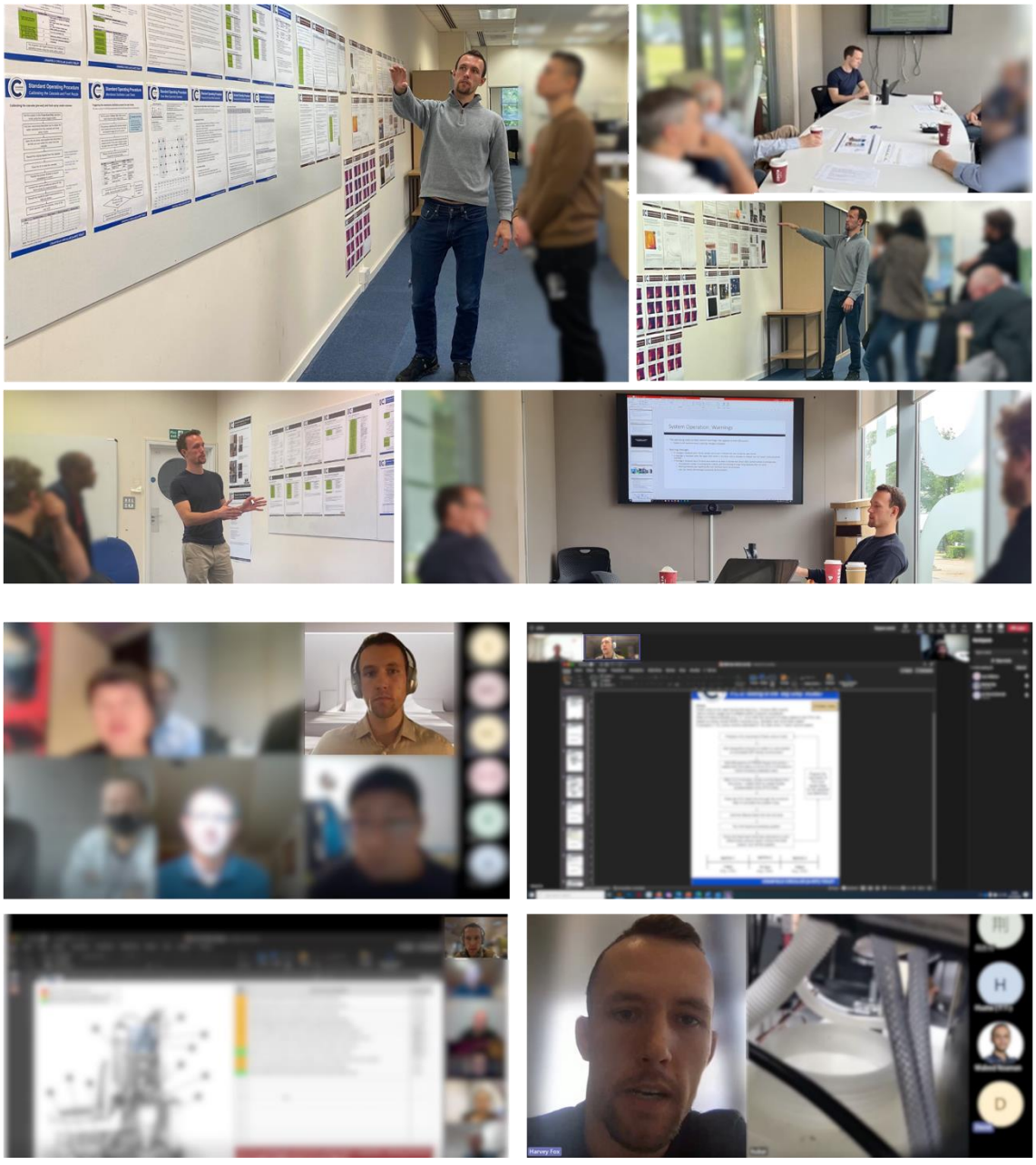
Appendix A – Data Management

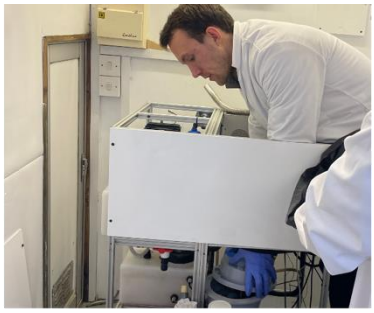
Secure Microsoft SharePoint/Teams portals were used as online repositories to store and transfer data between partners. These are private, invite-only repositories. All users are required to set-up two-factor authentication for account security. The SharePoint portals were set-up through Cranfield University's network with guidance from IT admins. The creation of these portals through the Universities network applies the correct settings and configurations for compliance and security within the University.

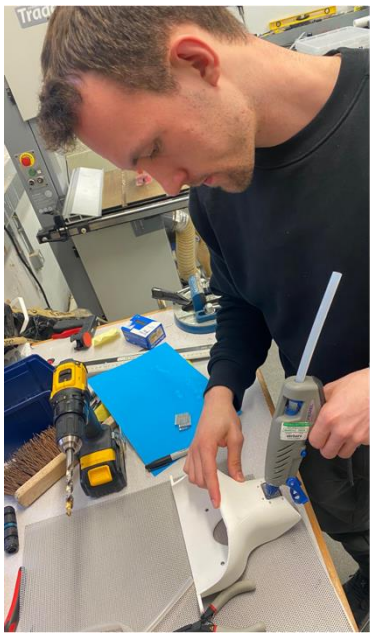


Appendix B – Photos of Project Activities

Appendix B shows photographs of the author partaking in various project-related activities across 2022-2023. This involves presenting to partners during visits, conducting online meetings with partners, trailer testing activities, and supervised lab activities. Some of the photos shown are unrelated to the specific research outlined in this thesis (e.g., trailer testing) but are used as evidence to demonstrate wider contributions to the project throughout time.



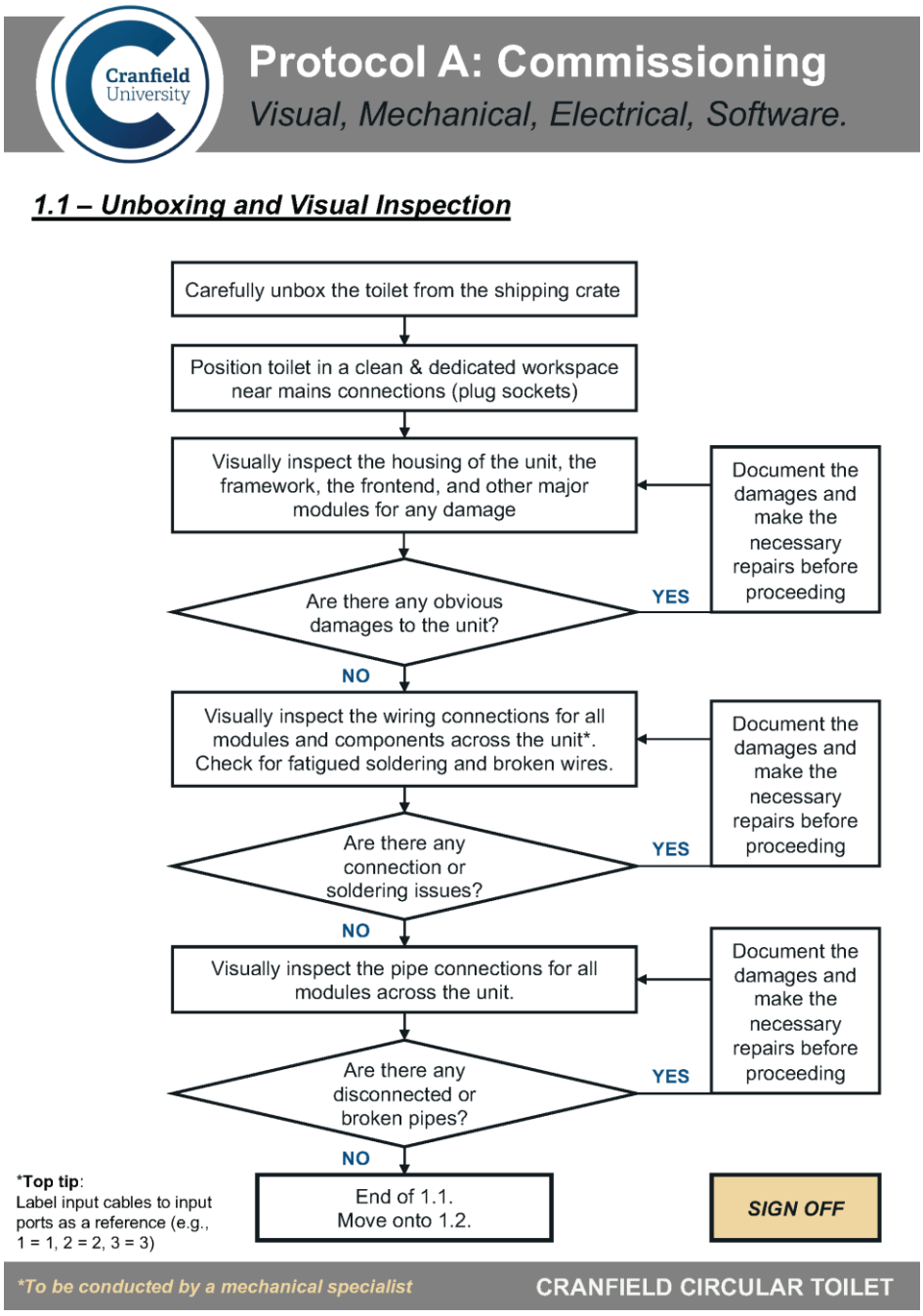




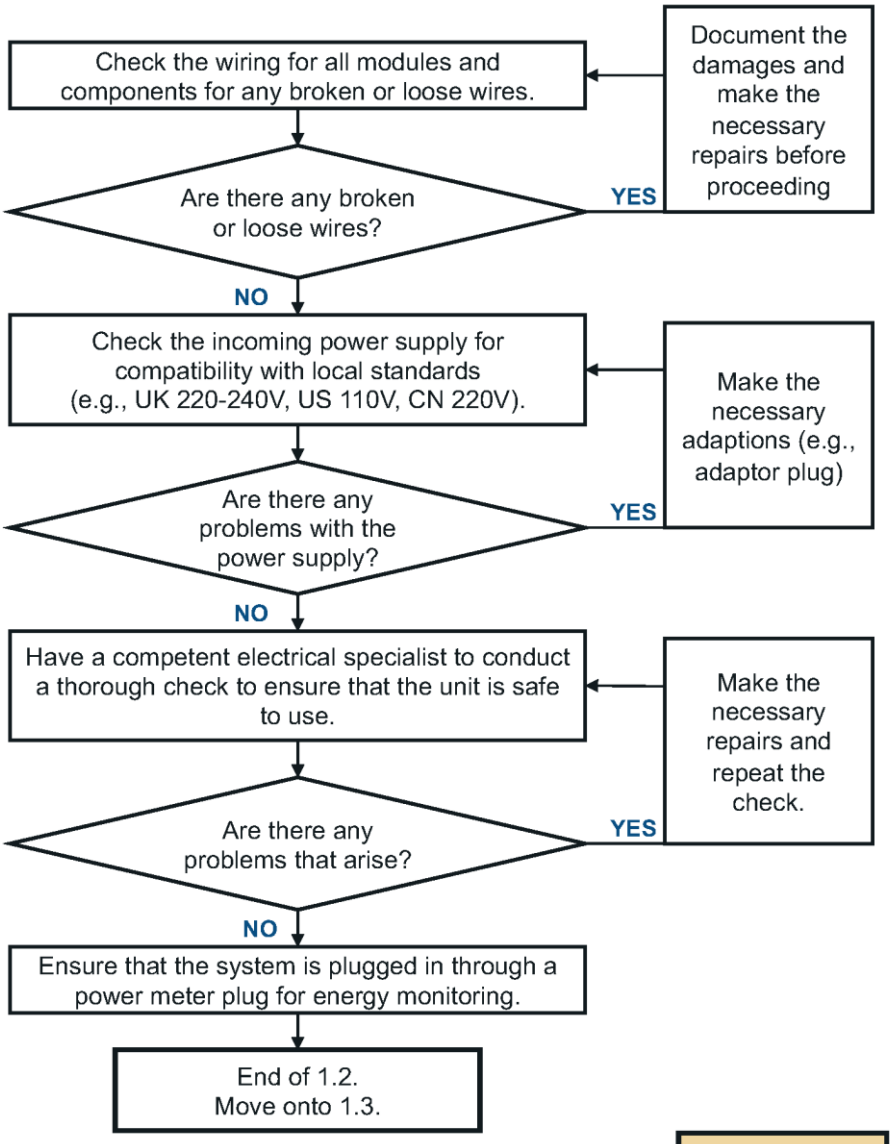
WASTE PUMP
WASTE PUMP

Appendix C – Examples of Synchronisation Protocol

Appendix C shows samples from the 60+ page synchronisation protocol applied and examined in Chapter 4. These documents were put together by the author with technical input from project engineers and leadership. The experimental procedures were created by the author (e.g., clean water experiment and toilet paper conveyance).



1.2 – Electrical Compliance Commissioning



SIGN OFF

1.4.1. – Output Devices Check

The output device check is the first of four checks.
It will check that the output devices across the system are connected and operational.

No.	Message on LCD	Duration (Sec)	Action
-	1) All Output Devices Check Testing:	3	Start of output devices check.
1	AugScrew Motor 1/12 -BWD 25 >>FWD+	2	Auger screw rotating forward.
	AugScrew Motor 1/12 -BWD<< -17 FWD+	2	Auger screw rotating backwards.
	AugScrew Motor 1/12 -BWD 0 FWD+	2	Auger screw STOP.
2	Evacuation Pump 2/12 -BWD 25 >>FWD+	2	Evacuation pump flowing forwards.
	Evacuation Pump 2/12 -BWD<< -17 FWD+	2	Evacuation pump flowing backwards.
	Evacuation Pump 2/12 -BWD 0 FWD+	2	Evacuation pump STOP.
3	Toilet Cl. Pump 3/12 @ Pan Front Nozzle	2	Toilet cleaning pump activated with valve open for front nozzle.
	Toilet Cl. Pump 3/12 @ Pan Back Cascade	2	Toilet cleaning pump activated with valve open for cascade.
	Toilet Cl. Pump 3/12 @ Bowl Left Nozzle	2	Toilet cleaning pump activated with valve open for left jet spray.
	Toilet Cl. Pump 3/12 @ Bowl Right Nozzle	2	Toilet cleaning pump activated with valve open for right jet spray.
	Toilet Cl. Pump 3/12 Stopped	2	Toilet cleaning pump STOP. Valves closed.
4	M.D. Dist Pump 4/12 Activated	2	Distillate loop pump activated.
	M.D. Dist Pump 4/12 Stopped	2	Distillate loop pump stopped.
5	M.D. Brine Pump 5/12 Activated	2	MD feed pump activated.
	M.D. Brine Pump 5/12 Stopped	2	MD feed pump stopped.
6	Radiator Fans 6/12 Activated	2	Radiator fans activated.
	Radiator Fans 6/12 Stopped	2	Radiator fans stopped.
7	Torrefac. Motor 7/12 -BWD 25 >>FWD+	2	Torrefaction motor rotate forwards.
	Torrefac. Motor 7/12 -BWD<< -17 FWD+	2	Torrefaction motor rotate backwards.
	Torrefac. Motor 7/12 -BWD 0 FWD+	2	Torrefaction motor STOP.
8	MD Peltier Unit 8/12 Activated	2	Peltier unit activated.
	MD Peltier Unit 8/12 Stopped	2	Peltier unit stopped.

Turn to next page to continue 1.4.1.

Protocol B: Liquids

Uploading the Code and LCD Display

Upload the **PROVIDED SKETCH** to the control board via the USB cable.

Observe the LCD display for these prompts:

Message on LCD	Duration (Sec)	Action
Cranfield University Circular Toilet	3	Describing the prototype.
Test Filename: XXXXXXXX	3	Name of Arduino Sketch uploaded to the control box.
Is Storage Tank Full And Toilet Lid Down?	N/A	Prompting the user to fill the storage tank and close the lid before starting the system processes.

Ensure that the toilet lid is closed.

Before filling the storage tank, ensure that the outlet port is connected to a drainage pipe.

Fill the storage tank with tap water until it reaches the overflow weir port.

Allow the tank to naturally settle as any excess water exits via the drainage pipe.

Press the yellow toggle button on the underside of the control box to progress to the operating mode menu.

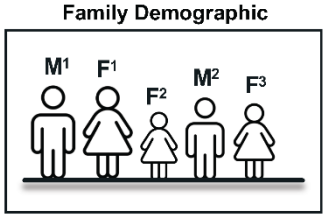
Message on LCD	Duration (Sec)	Action
Toilet Sys Standby AM: 0 No.Uses:0/1	5	Toilet system on standby (no ongoing processes). AM: Auger screw motor's speed (byte format). No. Uses: Number of toilet visits before starting an evacuation.
Sys Operation Mode: 1) Front-End Only	5	Front-end processes only.
Sys Operation Mode: 2) Membr. Dist. Only	5	Membrane distillation process only.
Sys Operation Mode: 3) Front-End + M.D.	5	Frontend and membrane distillation processes.

The engineer can toggle between the 3 different operating modes using the same yellow button.

Protocol B: Liquids

Clean Water Experiment Overview

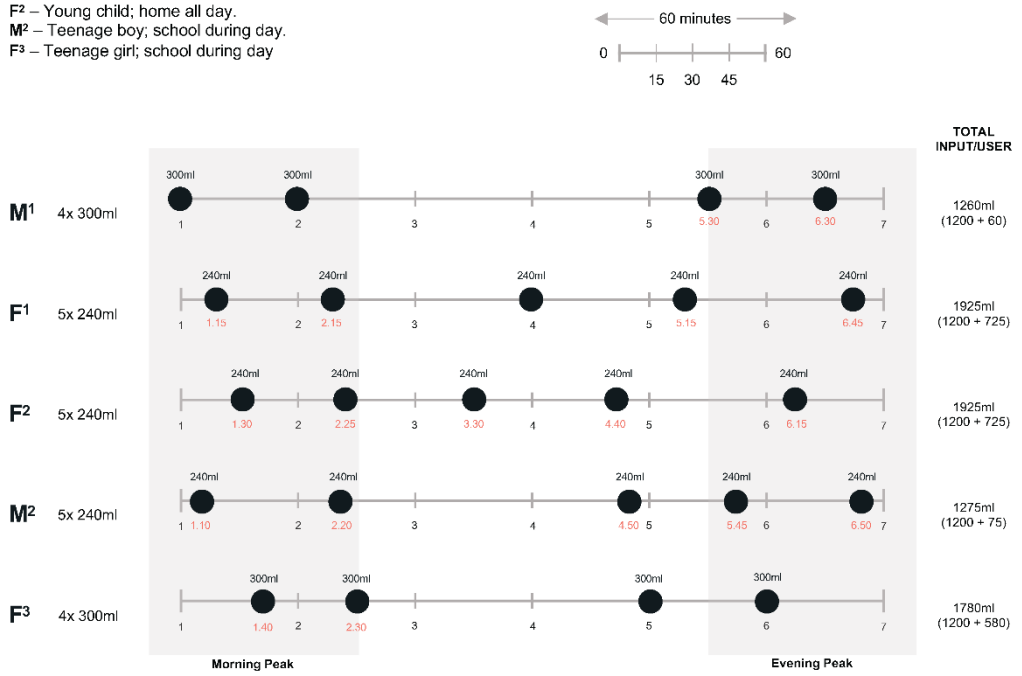
Family Demographic



Simulated Archetypes:
M¹ – Father; work during the day.
F¹ – Mother; home all day.
F² – Young child; home all day.
M² – Teenage boy; school during day.
F³ – Teenage girl; school during day

Total urine input per person per day: 1200ml/user
Urination event volume: 240 or 300ml/user
Pre wetting volume: 15ml~/open
Pan cleaning flush volume (short press): 65ml~/press

Male behavior sequence:
Lift lid → Pre wet (15ml~) → Urination → Close lid.
Female behavior sequence:
Lift lid → Pre wet (15ml~) → Urination → 2x short press (65+65=130ml~) → Close lid.



TIME	1.00	1.10	1.15	1.30	1.40	2.00	2.15	2.20	2.25	2.30	3.30	4.00
VOLUME	300ml	240ml	240ml	240ml	300ml	300ml	240ml	240ml	240ml	300ml	240ml	240ml
PERSON	M¹	M²	F¹	F²	F³	M¹	F¹	M²	F²	F³	F²	F¹
FLUSH	0	0	2	2	2	0	2	0	2	2	2	2

TIME	4.40	4.50	5.00	5.15	5.30	5.45	6.00	6.15	6.30	6.45	6.50
VOLUME	240ml	240ml	300ml	240ml	300ml	240ml	300ml	240ml	300ml	240ml	240ml
PERSON	F²	M²	F³	F¹	M¹	M²	F³	F²	M¹	F¹	M²
FLUSH	2	0	2	2	0	0	2	2	0	2	0

CRANFIELD CIRCULAR TOILET

Protocol B: Liquids

Preparing for Clean Water Experiment

Preparation for Clean Water Family Simulation Experiment

This will be a controlled experiment conducted in a lab environment.
The value of conducting this test is to emulate how the toilet would react in a family household setting (i.e., heavier use in the morning and evening, with less use during the day).

Experimental overview:

- The experimental simulation will run for **6-hours** (e.g., 9am-3pm).
- A family of 5 (2 males, 3 females) will be simulated.
- There will be a total of 23 drops.
- Each person will input a total of 1.2 liters (without pre-wet or front nozzle).
- Each drop will either be 240 (5x) or 300ml (4x).
- The lid will be opened for each drop – this will trigger the 15ml pre-wet.
- The 3 female users will use the 'short button press' twice (2x) each drop.
- The 2 male users will not use any button press.
- The total calculated input into the system is 8165ml (8.165L).

The engineer(s) will need access to:

- A clean water source (e.g., tap water).
- Measuring instruments to prepare input drops (up to 300ml).
- Drop schedule tracker (time, vol, no. of flushes).
- Measuring instrument to record distillate output.

To-do before starting:

- Completely drain the brine tank.
- Open and close the ball valve to release trapped fluids.
- Refill the distillate tank to the overflow outlet port and let it settle.

Protocol B: Liquids

Measurements for Clean Water Experiment

Data Collection for the Clean Water Experiment

The data collected from the family simulated clean water experiment will contribute towards synchronization efforts between all partners.
Please record the data carefully and with the intent for cross-comparison among all those conducting the experiment.

Measurements for when the MD process begins

Local Time	Time (min)	CSIT (°C)	CSOT (°C)	HSIT (°C)	HSOT (°C)	Notes
	0					
	10					
	20					
	30					
	40					
	50					
	60					
	70					
	80					
	90					
	100					
	n					

Note: CSIT = cold side inlet temperature. CSOT = cold side outlet temperature. HSIT = hot side inlet temperature. HSOT = hot side outlet temperature.

Measurements for MD activation and completion

	MD Start Time	Lower Float Switch Down	MD Completion Time	Total Time Taken
Local Time				
LCD Time	00:00			

MD Start Time: The time (local time + LCD time) that the MD process started.
Lower Float Switch Down: The time (local + LCD) that the lower float switch goes down (move to Process 4).
MD Completion Time: The time (local time + LCD time) that the MD process finishes.
Total Time Taken: The minutes:seconds reading provided by the LCD display and/or difference in local time.

Note: Each time the MD process is triggered by a drop, the above two tables should be filled in throughout the duration of the MD process.

Description of the Torrefaction (TF) Process [Continued]

Based on the information provided on the previous page, the TF process's operation is described as follows:

Operation When Below the Temperature Range (e.g., Below TFTemp3 – Minimum Heating Temperature):

- The heating is controlled by turning the heat clamp ON and OFF for set times (shown as 5 and 2.5 seconds in the operations table) via looping between phases 0 and 1 (in the operations table).
- The motor is rotating backwards (anti-clockwise) to churn the solids in the chamber.
- No other devices are turned on in these phases.

Operating When Within the Temperature Range (e.g., Between TFTemp3 – Minimum Heating Temperature and TFTemp2 – Minimum Heating Temperature):

Below the Target Temperature
- The heating is controlled by turning the heat clamp ON and OFF via looping between phases 2 and 3 for set times (shown as 5 and 2.5 seconds in the operations table).
- The motor is rotating forwards (clockwise).
- The air pump and radiator fans are turned ON at maximum speed.

Above the Target Temperature
- When in phase 4 (in the operations table), the motor is rotating forward (clockwise).
- The air pump and radiator fans are turned ON at maximum speed.
- The heat clamp is turned off as the target temperature is met or exceeded.

Operating When Above the Temperature Range (e.g., Above TFTemp2 – Maximum Heating Temperature):

- When in phase 5 (in the operations table), the motor is rotating forward (clockwise) at a slightly higher speed, the air pump and radiators fans are turned ON at maximum speed, and the heat clamp is turned OFF due to the target temperature being exceeded.

Additional Information:

Radiator Fans
- The radiator fans functionality is shared between the Liquids and Solids processing operations.
- The fans will be turned ON whenever the command is given from their respective operations.

**References to 'clockwise' or 'anti clockwise' are from the perspective as if the individual was standing in front of the toilet (frontend).

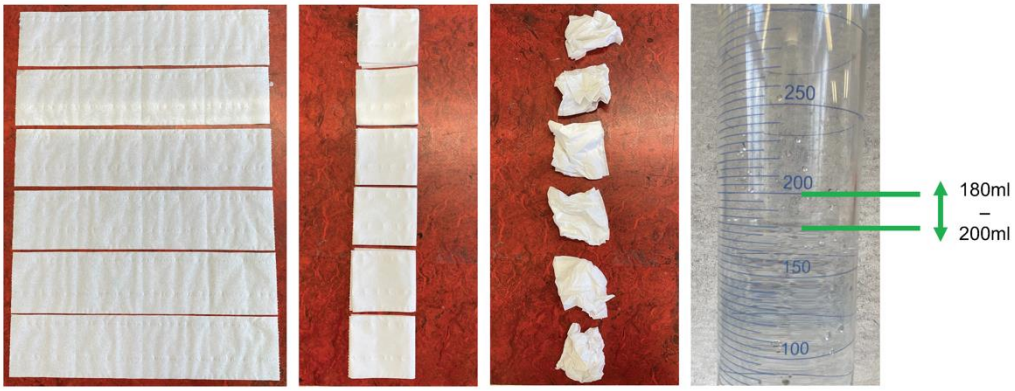
Preparing for Conveyance of Toilet Paper Experiment

This experiment is conducted to successfully convey toilet paper from:
the frontend → into the torrefaction hopper → out into the char tray.

This is an **ACCELERATED** experiment conducted to demonstrate *throughput* only.

Experimental Assumptions for Each Drop:

- End users will use 4 sheets of 2-ply toilet paper each 'wipe'.
- The end users will conduct 6 'wipes' during the defecation event.
- This will produce 24 sheets of toilet paper for each defecation event.
- A 'urination' event will occur in parallel producing between 180–200ml (water for wetting).



6 x 4 sheets | 6 x 4 sheets folded | 6 x 4 sheets crumpled | 180–200ml of water per event

PLEASE NOTE: The brine/hot tank will need to be monitored during the experiment and manually drained when reaching high volumes to prevent it from overflowing. We will not be activating the liquids subsystem during this experiment.

We are purposely using several more toilet paper sheets than the 12-sheets defined in the ISO 30500 standards as this is more realistic to an uncontrolled environment (real-world) and is aligned to the accelerated testing procedure detailed within this protocol.

Observing the Conveyance of Toilet Paper – Inside the Hopper

- As the toilet paper reaches the top of the auger screw, it will fall into the torrefaction hopper.

First Toilet Paper Drop into the Hopper

Hopper after Approx. 4 Drops

4x Speed Video of Inside the Torrefaction Hopper (Fully Loaded)

Appendix D – Example of Instruction Manual

Appendix D serves as an example of knowledge transfer and communication across partners during technology development. The author created and designed this document with minor technical input from project engineers.

Cranfield University

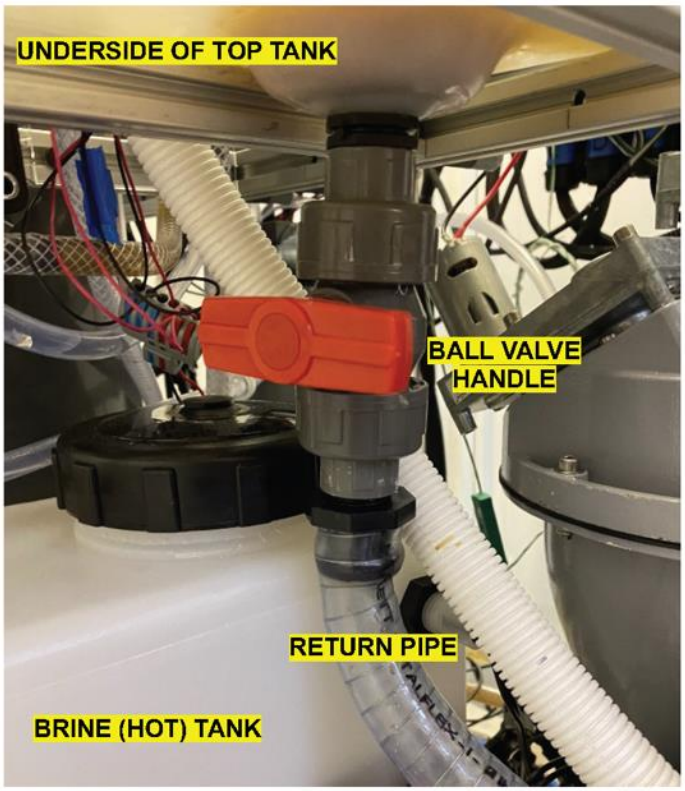
Instructions Manual

Operating the Ball Valve to Clean Top Tank Filter

Document created on 13th May 2023 (V2.X+)

Overview

- The ball valve is positioned under the filter in the top tank and is connected to a pipe which returns to the frontend.
- Its purpose is to clean the solids from the inside of the filter and return them to the frontend collection tank for processing.
- This is done by opening the ball-valve and flushing water through the filter - which will encourage the solids to drop.



CRANFIELD CIRCULAR TOILET

Instructions Manual

Operating the Ball Valve to Clean Top Tank Filter

CLOSED
POSITION

OPENED
POSITION

When to Open the Ball Valve?

1. When the filter shows visual signs of fouling;
2. Periodically during operation to keep the filter clean;
3. After heavy use of fecal defecation (Type 5-7 Bristol stools);
4. When the filter has not been actively used for a long duration of time and has dried out.

Signs When the Filter Begins to Struggle

1. The liquids in evacuation between the mini-puppy pump (evacuation pump) and upper tank is struggling to move;
2. The liquids in evacuation between the mini-puppy pump has completely stopped moving.

Types of Filters for the Top Tank

1. Filter with membrane on the outer wall – not recommended;
2. Filter with membrane on the inner wall – good option;
3. Filter with membrane running throughout – good option.

Filter type [1] are very difficult to clean (membrane on the outer wall), whereas filter type [2 & 3] can be flushed more easily.

Filter type 3 (left) and type 2 (right) – 190mm

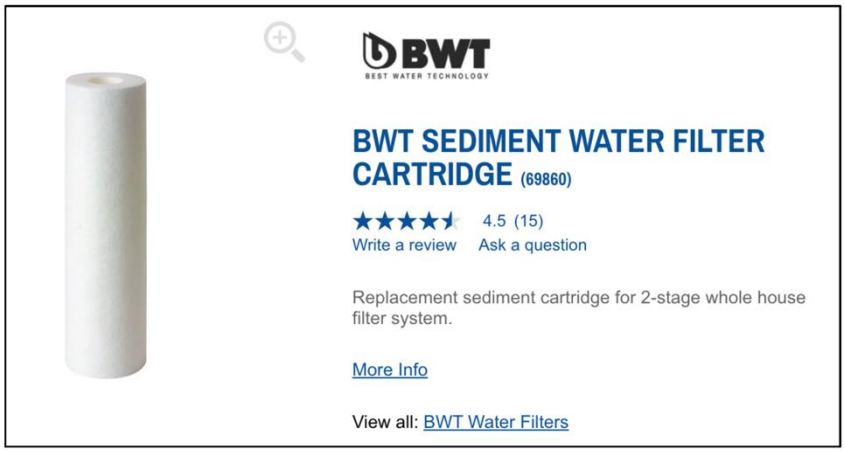
Filter type 2
(membrane on inner wall)

Filter type 3
(filter running throughout)

Filter Currently in Use at Cranfield

- The Cranfield team are currently using a 5-micron sediment water filter cartridge in their system.
- This filter is spun using polypropylene meaning that the membrane is all throughout the depth of the filter.
- To fit the filter into the tank, the team peel the membrane to fit inside the tank (using a sharp blade).

"The SB range of cartridge filters are classified as nominal depth filters, meaning they filter out a percentage of the particles of its given micron rating and does this through the depth of the filter." – BWT Factory (Email)

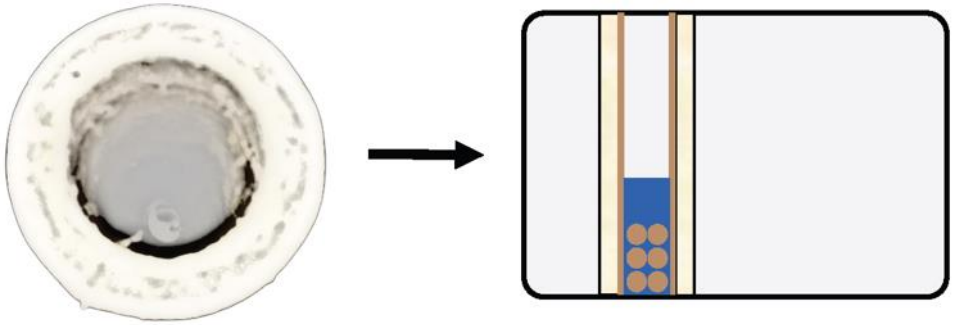


https://www.screwfix.com/p/bwt-sediment-water-filter-cartridge/69860

Example of Fouling in the Top Tank Filter

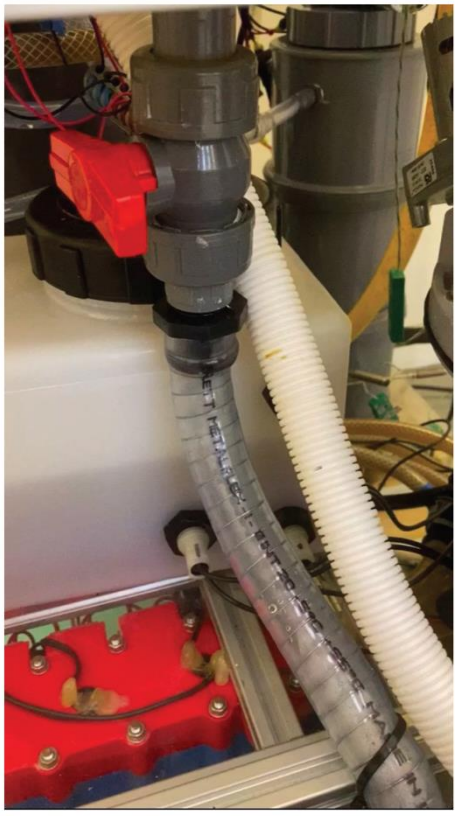
Top-down view of filter

The photo shows that the filter in the top tank has fouled and it is storing solids and liquids at the bottom (not allowing liquids to pass through).



Graphic of inside filter

Opening the Ball Valve WITHOUT an Evacuation



Video of opening ball valve

This video shows the ball valve being opened and a small amount of liquid being released.

This is without an evacuation of liquids to encourage the solids to break off the walls.

Even though the ball valve is open, we cannot see through the filter. This shows that solids are blocked at the bottom of the filter.

Filter after opening ball valve without an evacuation

Opening the Ball Valve WITH an Evacuation (First)

Video of open ball valve evacuation

This video shows the ball valve in an OPEN position with the first liquid evacuation occurring.

The lid was opened, the defecation button (long press) was pressed twice, and the lid was closed.

The first liquid evacuation broke some of the solids from the bottom of the filter, but there were still some solids remaining.

Filter after first evacuation

Opening the Ball Valve WITH an Evacuation (Second)

Video of open ball valve evacuation

This video shows the ball valve in an OPEN position with the second liquid evacuation occurring.

The lid was opened, the defecation button (long press) was pressed twice, and the lid was closed.

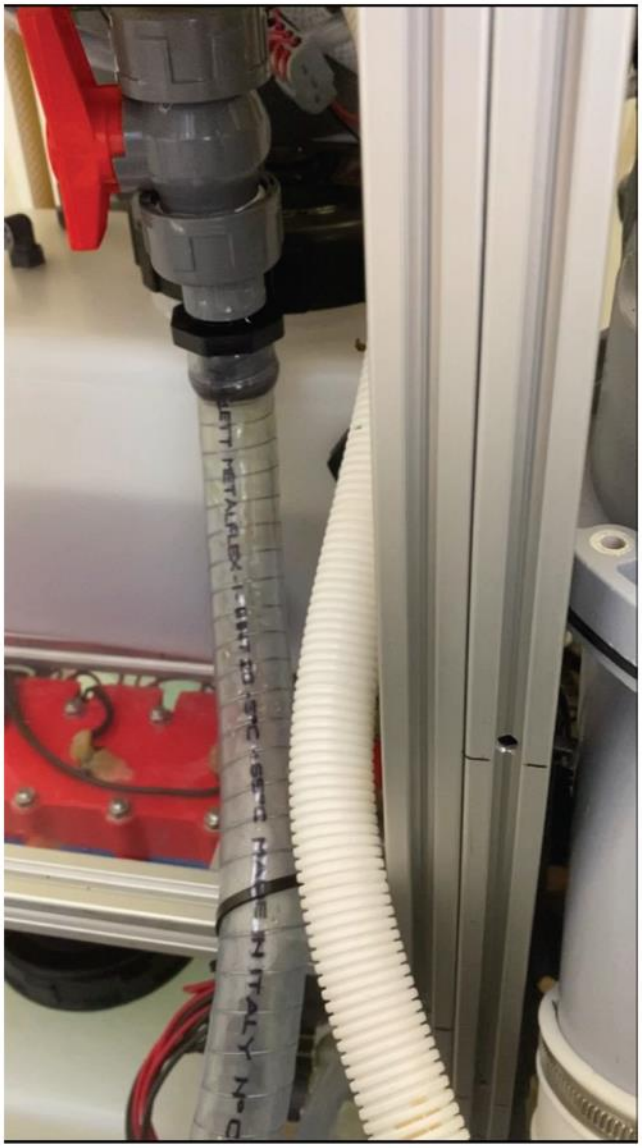
The second liquid evacuation broke off all the solids at the bottom of the filter allowing us to see straight through the filter.

Filter after second evacuation

Instructions Manual

Example of Ball Valve in Action

Slow Motion Video of Solids Falling from the Filter During the Second Liquids Evacuation Process



CRANFIELD CIRCULAR TOILET

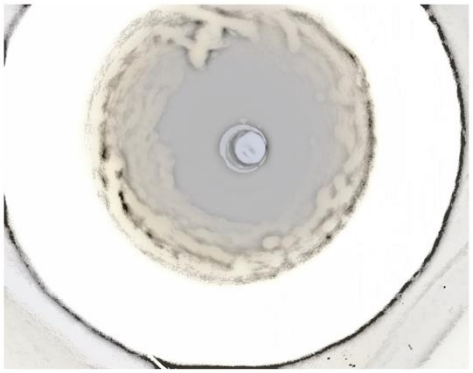
Opening the Ball Valve WITH an Evacuation (Third)

Video of open ball valve evacuation

This video shows the ball valve in an OPEN position with the third liquid evacuation occurring.

The lid was opened, the defecation button (long press) was pressed twice, and the lid was closed.

The third liquid evacuation allowed for any finer debris to fall off – but generally was not needed as most of the clearance had been made by the second liquid evacuation.



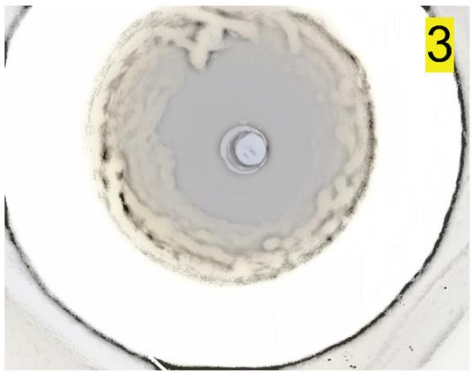
Filter after third evacuation

Stages of Filter Cleaning Using Ball Valve

Filter after opening ball valve without an evacuation

Filter after first evacuation

Filter after second evacuation



Filter after third evacuation