CRANFIELD UNIVERSITY

Jan Hennigs

Prototype Testing in Product Development: The Case of the Nano Membrane Toilet

SWEE
PhD in Water

PhD
Academic Year: 2019 – 2020

Supervisor: Sean Tyrrel
Associate Supervisor: Alison Parker
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ABSTRACT

The provision of safely managed sanitation in densely populated urban settlements of cities in low- and middle-income countries poses complex challenges. To address these challenges, Cranfield University is developing the Nano Membrane Toilet, a novel standalone household-level sanitation technology that operates off the grid and safely treats human waste while having an aspirational design. Developing such a complex novel product requires testing a multitude of prototypes in numerous ways. Since designing, building and testing the prototypes is often done by separate teams of various disciplines, the entire testing process requires a considerable amount of planning and communication. This thesis not only reports on field trials and laboratory testing of two prototypes of the Nano Membrane Toilet, but also investigates the under-explored field of planning and communicating prototype tests for complex product development processes. In a first trial, a prototype mechanical toilet flush is assessed in user tests and lab tests. It is shown to be liked by users of Urine Diversion Dehydration Toilets, and it appears to perform best when lubricated and with a silicone rubber with oil-bleed-effect for its swipe. A second round of tests explores settling and displacement as means of solid-liquid separation in the Toilets collection tank. Toilet paper is shown to inhibit settling of faeces, while a conical tank geometry promotes it. From a literature review and subsequent interviews with experts in prototype testing, a visual tool for planning and communication prototype tests for the Nano Membrane Toilet is developed, validated and refined into a generally applicable, modular version. This modular tool can be used to produce customised visual testing strategies for a variety of product development processes, to facilitate planning and communicating testing activities across interdisciplinary teams.

Keywords:

Sanitation, Reinvent The Toilet Challenge, Interdisciplinary Communication

ACKNOWLEDGEMENTS

I dedicate this thesis to my daughter, Emmeline Luise. You were the reason I finished on time!

I also want to thank everyone that helped me during the last three years on this journey of writing a PhD thesis:

First of all, I want to thank my superhero supervisors, Sean Tyrrel and Alison Parker. You chose me to join the NMT project and guided me through my research. You always found a positive interpretation of results and helped me turn my vague ideas into comprehensible text. I wouldn't have been able to write this thesis without you!

The fact that conducting Human User Testing on a toilet prototype was not only interesting and successful but also a lot of fun can be attributed to the members of Work Package A, the A-Team. Anju, Dani, and Kristin, you were brilliant teammates and I am grateful for your help, during and beyond the user testing phase!

Similarly, my time in South Africa was made forever-memorable by the amazing members of the Pollution Research Group at UKZN. You made working on the other side of the planet the easiest thing in the world by inviting me into your family of poop-scientists, where no day goes without laughter. Thank you!

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Research may be the most important part of a PhD, but it is not everything. Having a thriving social life is a good way to maintain one's mental health during such an intense experience. This is why I am incredibly grateful for the lunch group, which started out as a handful of people and has grown to the point where we need to take over other tables. The random discussions about sandwich definitions, the science of holy water, and all sorts of faecal matter have always been an effective way to clear the mind from monotonous workdays. In many of you, I have found not only colleagues, but also great friends!

Furthermore, I also want to show my gratitude to all the members of CWSI who always took the time to give advice and help where needed. The open, nurturing and supportive culture here should be an example for research institutes everywhere.

Of course, I would not be at this point – or here at all – without my parents. Mama, Papa, you have always encouraged me to continue my education. You supported me materially, but foremost emotionally, while I moved further and further away from you to study more and more bizarre subjects. Without your love and support I could not have become the person I am today, and I am forever indebted to you!

The person I have to thank the most, however, is my wife! Bron, I can't even begin to put into words what you mean to me. If all of this research were in vain, I would still do it all again, because it brought me to you. The many twists and turns my research took might have been enough for me to give up, had it not been for your support. Being able to come home to you, always have someone to talk to and have the greatest fun with has kept me sane and happy throughout a stressful time. I am thrilled to spend the rest of my life with you, and the family we built!

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LIST OF ABBREVIATIONS

ALT	Accelerated Life Testing
ANOVA	Analysis of Variance
BMGF	Bill & Melinda Gates Foundation
BSC	Bristol Stool Chart
COD	Chemical Oxygen Demand
dCOD	Dissolved Chemical Oxygen Demand
DOE	Design of Experiments
DUR	Durability Testing
F	Frequency (of Defecation)
HALT	Highly Accelerated Life Testing
HnS	Health and Safety
HTC	Hydrothermal Carbonisation
Int. Std.	International Standard
ISO	International Organization for Standardization
LMIC	Low- and Middle Income Countries
NMT	Nano Membrane Toilet
PD	Product Development
PRG	Pollution Research Group
REL	Reliability Testing
RTTC	Reinvent The Toilet Challenge
SDG	Sustainable Development Goals
SMF	Synthetic Menstrual Fluid
SOB	Silicone Rubber with Oil-Bleed effect
SU	Synthetic Urine
TP	Toilet Paper
TS	Total Solids
UCD	User Centred Design
UDDT	Urine Diversion Dehydration Toilet
UKZN	University of KwaZulu-Natal
UN	United Nations
UNICEF	United Nations Children’s Fund
USFDA	United States Food and Drug Administration

V	(Tank) Volume
VIP	Ventilated Improved Pit Latrine
VS	Volatile Solids
WHO	World Health Organisation

1 Introduction

Abbreviations: BMGF – Bill & Melinda Gates Foundation; COD – Chemical Oxygen Demand; HTC – Hydrothermal Carbonisation; HUT – Human User Testing; LMIC – Low- and Middle Income Countries; NMT – Nano Membrane Toilet; PD – Product Development; RTTC – Reinvent The Toilet Challenge; SDG – Sustainable Development Goals; UDDT – Urine Diversion Dehydration Toilet; UN – United Nations; UNICEF – United Nations Children's Fund; WHO – World Health Organisation

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1.1 The Sanitation Crisis – a global phenomenon

According to the most recent report of the World Health Organization (WHO) and United Nations Children's Fund (UNICEF) Joint Monitoring Programme for Water Supply Sanitation and Hygiene, 45% of the worldwide population used safely managed sanitation services in 2017, while it was only 22% in the year 2000 (WHO and UNICEF, 2019). While this should be celebrated, it means that more than half of the world's population still does not have access to safely managed sanitation. This does not only concern low- and middle-income countries (LMIC): even in Europe and North America, only 76% of the population had access to safely managed sanitation (WHO and UNICEF, 2019).

Sanitation is defined by the WHO (2018) as "*access to and use of facilities and services for the safe disposal of human urine and faeces*",

and **safely managed sanitation** is further defined as "*use of improved*[1] *facilities that are not shared with other households and where excreta are safely disposed of in situ or transported and treated offsite*" (WHO and UNICEF, 2017).

Lack of safely managed sanitation bears numerous risks, like groundwater pollution (Graham and Polizzotto, 2013) and infection with gastrointestinal diseases (Prüss-Ustün *et al.*, 2014). Environmental enteric dysfunction, a

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[1] "Improved facilities include flush/pour flush to piped sewer systems, septic tanks or pit latrines; ventilated improved pit latrines, composting toilets or pit latrines with slabs."(WHO and UNICEF, 2017)

subclinical state of intestinal inflammation, has been linked to poor sanitation and is believed to be a cause of child stunting (Budge *et al.*, 2019). When lacking access to sanitation and being forced to defecate in the open, women and girls are more likely to be victims of sexual violence (Jadhav, Weitzman and Smith-Greenaway, 2016). People who menstruate are more likely to miss school if they cannot manage their period in safe sanitation facilities (Miiro *et al.*, 2018). Increasing sanitation coverage could help reduce these risks. The United Nations (UN) have recognised the need for better sanitation and included it in their *Sustainable Development Goals (SDG)*, with *SDG number 6: Ensure availability and sustainable management of water and sanitation for all* (UN General Assembly, 2015).

Ceramic water flush toilets connected to centralised sewer systems and municipal wastewater treatment facilities generally fulfil the conditions of safely managed sanitation, and are likely the most popular and common sanitation technology in high income countries (Dunlap, 2017). In many LMIC, however, the majority of the growing population lives in densely populated, often informal urban settlements (Castells-Quintana and Wenban-Smith, 2019). Providing piped water and sewer connections to all inhabitants of these cities is often prohibitively expensive (Dodane *et al.*, 2012; Daudey, 2017), especially as many LMIC are in water-scarce regions of the earth (Heath, Parker and Weatherhead, 2012). In addition, centralised sewer systems and wastewater treatment plants require high amounts of water and energy to function properly (Metcalf & Eddy Inc. *et al.*, 2014), and climate change events like droughts and floods are expected to disproportionately affect the poor in LMIC (Heath, Parker and Weatherhead, 2012). Hence more sustainable sanitation solutions are required for these populations.

1.1.1 State of the Art of Non-sewered Waterless Urban Sanitation

Common sanitation solutions that require neither water nor sewer connection are pit latrines and Urine Diversion Dehydration Toilets (UDDT, a variation of the pit latrine) (Seleman and Bhat, 2016). However, the absence of sewers necessitates complex faecal sludge management procedures that pose several problems

(Strande, Ronteltap and Brdjanovic, 2014): Pits require periodic emptying, which is not always carried out safely, but rather by hand and without proper personal safety equipment. Once removed from the pit, the faecal sludge may not be transported and treated safely, but rather discharged illegally, into the environment (Jenkins, Cumming and Cairncross, 2015; Semiyaga *et al.*, 2015). In some cases, it is directly applied as crop fertiliser, posing a significant health hazard (Mallory, Crapper and Holm, 2019).

To the users of pit latrines and UDDT, these toilets are “poor people’s toilets” that are inferior to water flush toilets (Mkhize *et al.*, 2017). The pedestals of these toilets, often made from plastic (Personal communication with Jacques Rust, Envirosan, Republic of South Africa), can be seen as dirty, uncomfortable, and dangerous for children, as they can fall into the pit (Roma *et al.*, 2013; Mkhize *et al.*, 2017).

1.1.1.1 The Reinvent The Toilet Challenge

To address the challenges of non-sewered, waterless urban sanitation by developing novel technologies, the Bill & Melinda Gates Foundation (BMGF) initiated the *Reinvent The Toilet Challenge* (RTTC) in 2011. They awarded generous grants to researchers and inventors to “create a toilet that:

- Removes germs from human waste and recovers valuable resources such as energy, clean water, and nutrients,
- Operates “off the grid” without connections to water, sewer, or electrical lines,
- Costs less than US$ 0.05 per user per day,
- Promotes sustainable and financially profitable sanitation services and businesses that operate in poor, urban settings, [and]
- Is a truly aspirational next-generation product that everyone will want to use – in developed as well as developing nations.” (BMGF, 2013)

The challenge sparked a series of Product Development (PD) projects: At the Beijing Reinvented Toilet Expo in November 2018, 11 reinvented toilet and sanitation technology designs were presented, alongside four *omniprocessors*, capable of treating various faecal sludge waste streams (BMGF, 2018). However, to date none of the reinvented toilets have been able to claim that they meet all of the conditions of the RTTC. Instead, research and development are still ongoing to develop affordable, safe, and sustainable sanitation technologies. Some of these PD projects are:

The Eco-San Toilet, developed at the California Institute of Technology (Caltech):

The technology developed at Caltech is a system for electrochemical treatment of toilet flush water. Common ceramic water flush toilets are used as *user interface*, and solar panels provide the electric energy required for the pumping, maceration, and electrolysis of the flush water (Hoffmann, Cho and Cid, 2014). The system has been field tested successfully in the United States, India, and China. The flush water was disinfected and chemical oxygen demand (COD), ammonia, and colour could be reduced. The treated water could then be reused for flushing (Cid, Qu and Hoffmann, 2018). Among others, the researchers at Caltech have investigated the system's potential for phosphate recovery (Cid, Jasper and Hoffmann, 2018), hydrogen production (Cho, Kwon and Hoffmann, 2014), and the formation of toxic by-products (Jasper, Yang and Hoffmann, 2017).

The Blue Diversion Toilet, developed at the Swiss Federal Institute of Aquatic Science and Technology (EAWAG):

The Blue Diversion Toilet is a squat toilet that uses water for flushing and provides handwashing water. Source separation allows for treatment of the flush- and handwashing water within the system, by means of a membrane bioreactor (Larsen *et al.*, 2015; Nguyen *et al.*, 2017; Ziemba *et al.*, 2018). Urine and faeces are stored for transport to further treatment. A prototype of the toilet has been field tested and found positive feedback among participants in an informal urban settlement in Kampala, Uganda (Tobias *et al.*, 2017).

Following this, EAWAG are now developing and field testing the *Blue Diversion Autarky Toilet*, in an effort to provide onsite treatment of the separated urine and faeces (Lienert and Udert, 2018). Urine will be stabilised with calcium hydroxide

(Randall *et al.*, 2016) and subsequently evaporated and concentrated to produce fertiliser (Bethune, Chu and Ryan, 2016). For faeces treatment, the process parameters of hydrothermal oxidation (Hübner, Roth and Vogel, 2016) are being investigated.

The NEWgenerator, developed at the University of South Florida (USF):

USF's NEWgenerator is an onsite wastewater treatment system, so much like Caltech's Eco-San system it can be connected to regular flush toilets. The system uses electricity provided by solar panels and treats the wastewater in an anaerobic membrane bioreactor. It has been successfully piloted in field tests in India (Bair *et al.*, 2015), and further tested in the Republic of South Africa, in an effort to commercialise the technology (Tyne, 2018).

The Neighbourhood-Scale Sewage Treatment System, developed at Duke University:

Duke University's system aims to treat the collected faecal sludge of ca. 1200 people by means of supercritical water oxidation, a process that sanitises the waste and does not require drying or additional fuel sources (Miller *et al.*, 2015). While currently no further peer-reviewed publications on this project are available, the researchers at Duke University publish monthly updates on their web page. They are currently optimising the technology's operating conditions (Duke University, 2018).

Hydrothermal Carbonisation, researched at Loughborough University:

Loughborough University is researching the treatment of faecal sludge through hydrothermal carbonisation (HTC), a process in which the faecal waste is sanitised and converted to char which can be used as fuel, and ammonia-rich liquor which can be turned into fertiliser (Afolabi and Sohail, 2016). Extensive studies have been carried out to investigate the process parameters of HTC using microwaves (Danso-Boateng *et al.*, 2013; E. Danso-Boateng, Holdich, *et al.*, 2015; E. Danso-Boateng, Shama, *et al.*, 2015; Eric Danso-Boateng *et al.*, 2015), the product chars have been characterised (Afolabi, Sohail and Thomas, 2017), and anaerobic digestion has been studied for treatment of the liquid product fraction (Nyktari *et al.*, 2017).

The Nano Membrane Toilet, developed at Cranfield University

One reinvented toilet that operates entirely without water is the Nano Membrane Toilet (NMT), invented by researchers at Cranfield University (Parker, 2014). In concept, the NMT looks similar to a water flush toilet (Figure 1-1). A dry, mechanical flush receives the human waste and transports it into a collection tank underneath (Tierney, 2017). From there, solids are transported and dewatered via an auger (E Mercer *et al.*, 2016), then dried and combusted (Onabanjo, Patchigolla, *et al.*, 2016). The liquid waste exits the collection tank over a weir and is treated in membrane processes, driven by the heat of the combustion (Hanak *et al.*, 2016; Kamranvand *et al.*, 2018). Theoretically, the NMT can operate without additional energy input (Onabanjo, Patchigolla, *et al.*, 2016) and would simply produce clean water and ash. With its sub-systems (Figure 1-1 a), or sub-products, the NMT as a whole can be considered a complex product (Afsarmanesh and Shafahi, 2013), as can be most of the other reinvented toilets. Developing complex products often is a complicated, multidisciplinary endeavour (Luo *et al.*, 2016), involving the construction and testing of numerous prototypes (Tahera, Eckert and Earl, 2015; Larsen *et al.*, 2016).

The NMT project started receiving funding from the BMGF in 2012 (BMGF, 2013) and continued to do so in several phases. The present work is part of phase 3, which comprises work packages on combustion and energy, membrane treatment, design, communications, routes to market, and Human User Testing (HUT). Mr. Hennigs was part of the HUT team, which was tasked with conducting prototype tests with real people using an NMT prototype as their toilet. The design team built a prototype for this purpose and cooperated with the HUT team to set up testing facilities. Upon analysis of the test results, the HUT team communicated design change recommendations to the testing team. This meant that a clear set of tasks was prescribed for the HUT team. The tested prototype was developed as result of previous design and testing processes that occurred before Mr. Hennigs joined the project, namely laboratory tests on the functionality of the mechanical toilet flush and user tests of a previous prototype This posed limitations on the research that Mr Hennigs could conduct within the project, namely tests that furthered the knowledge about the usability and user acceptance of the prototype built by the design team.

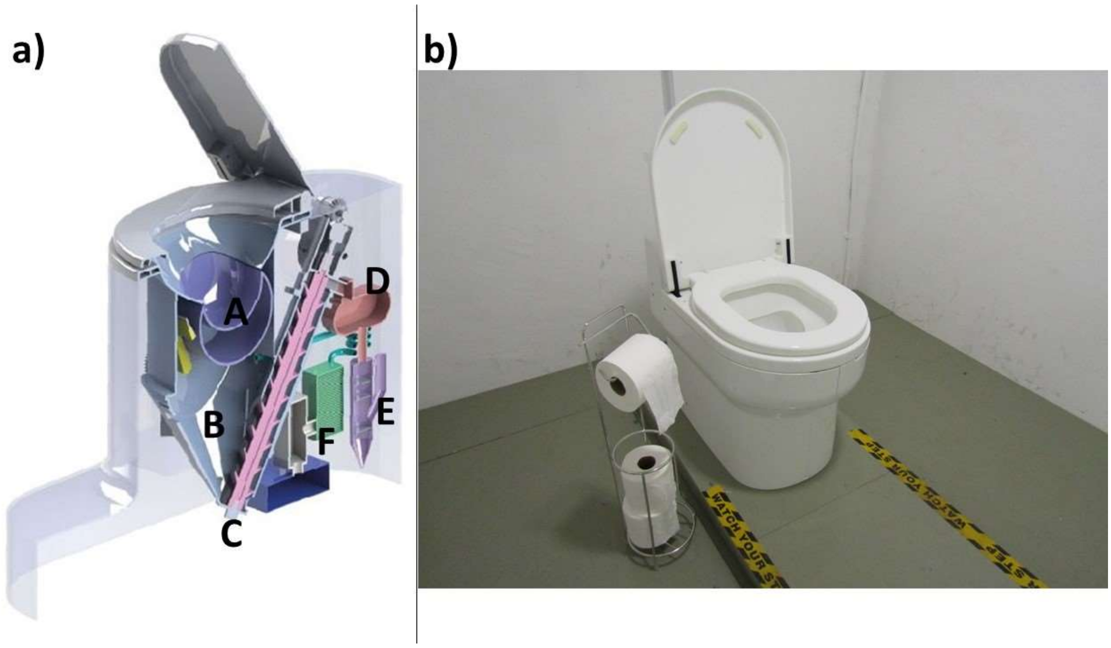

Figure 1-1: NMT. a) schematic drawing of its components: A - mechanical flush, B - collection tank, C - auger, D - dryer, E - combustor, F - membrane bundle; b) photograph of an NMT prototype for field testing.

1.2 Prototype testing and its role in Product Development

A **prototype**, broadly defined as "*approximation of the product along one or more dimensions*" by Ulrich and Eppinger (2016), can take various forms and have several functions. For example, prototypes can be virtual, like CAD models or process simulations, or physical, like foam block models, 3D printed objects, or fully functioning pilot-scale rigs (Tahera, Earl and Eckert, 2014). They can resemble the final product very closely (high *fidelity*), or only loosely (low *fidelity*) (Mccurdy *et al.*, 2006). Ulrich and Eppinger (2016) categorise four purposes of prototypes: learning, communication, integration, and milestones. This thesis, however, will mainly focus on the purpose of learning, which is achieved through testing prototypes: In a design thinking approach, prototypes are built, tested, iteratively refined, and validated throughout the PD process (Zeh, 2015), making them an essential aspect of product design, and consequently of the PD process. Prototyping is frequently featured in academic literature: Camburn *et al.* (2017), for example, present a thorough overview of the literature on prototyping strategies, techniques, and guidelines. The testing of prototypes, however, is rarely the focus of academic investigation (Tahera, Eckert and Earl, 2015).

1.2.1 Prototype testing: How is it done?

Testing is defined by the IEEE (1990) as "*activity in which a system or component is executed under specific conditions, the results are observed, and an evaluation is made of some aspect of the system or component*". While this definition was made for the context of software engineering, Tahera *et al.* (2019) adopt this definition for PD in general. Research on *testing strategies* tends to focus on optimising the time and number of prototype tests in PD (Thomke and Bell, 2001; Al Kindi and Abbas, 2010a; Qian *et al.*, 2010), but not on the types of tests that need to be conducted. Tahera, Eckert and Earl (2015) stress the importance of testing throughout the PD process and develop a PD process model that emphasizes this importance, but that unfortunately does not answer the question of '*How to test?'*, either.

As established earlier, the development of complex products like the NMT is a complicated, interdisciplinary process, and this pertains especially to the design, construction, and testing of prototypes. The lack of guidance on how to conduct prototype tests complicates the planning and communication of testing activities across multidisciplinary teams. Badly planned and communicated prototype tests are at risk of wasting time and resources by not providing the best possible information to improve the product's design. Tahera, Earl and Eckert (2014) bemoan that testing does not receive as much academic attention as other aspects of PD. They list examples of publications about testing as part of PD (Loch, Terwiesch and Thomke, 2001; Thomke and Bell, 2001; Lévárdy, Hoppe and Browning, 2004; Van Der Auweraer and Leuridan, 2005; Hoppe, Engel and Shachar, 2007), but specify that most consider only individual techniques.

Similarly, Batliner *et al.* (2018) lament that a lack of literature about general testing methodology complicates its consideration in engineering design curricula. It is likely that there is a wealth of knowledge about prototype testing for PD within companies that, unfortunately, remains tacit or informal (Sabeeh, Mustapha and Mohamad, 2017).

1.3 Aims and Objectives

Goal

In order to resolve the problems associated with poor sanitation, particularly in fast growing cities of LMIC, novel sanitation products like the NMT should be developed without unnecessary delay. Thus, prototype tests should be planned, communicated, and conducted as effectively and efficiently as possible.

To enable this goal, this thesis aims to:

1. Further the development of the NMT through prototype tests.

   Objectives:

   a) Plan and conduct tests of NMT prototypes
   b) Analyse the test results and make informed design recommendations based on the analysis

2. Investigate and formalise how prototype tests are planned and conducted for the NMT and other novel, complex products.

   Objectives:

   a) Review the literature about testing of prototypes and develop a literature-based tool to facilitate planning and communication of prototype tests for the NMT
   b) Collect and analyse tacit expert knowledge to gain further insight into prototype testing and to improve and generalise the tool for planning and communication of prototype testing.

1.4 Thesis Outline

Much like the development of the NMT and other novel sanitation technologies is highly multidisciplinary, this thesis' research applied several qualitative and quantitative methodological approaches. This is a thesis by paper, and thus, Chapters 2, 3, 4, and 5 are designed for publication as peer-reviewed research articles. The following chapters are outlined below and visualised in Figure 1-2.

To address objectives 1.a) and 1.b), the next chapter (Chapter 2) describes a set of tests conducted on a prototype of the NMT's mechanical toilet flush, a part of its front end. This comprises quantitative laboratory tests and qualitative field trials with user tests in an environment in which the NMT could likely be deployed. From the test results, design recommendations are derived to inform the next design iteration. This chapter has been published as a peer-reviewed article in *The Science of the Total Environment*. The prototype that was tested in this chapter was developed before the research for this thesis began, and while the tests yielded valuable information, the lack of a shared prototype testing strategy complicated the communication across the interdisciplinary teams collaborating during the field trials. Thus, the work on this chapter was influential in uncovering the knowledge gap about prototype testing in PD as illustrated in Section 1.2.1 and, in more detail, in Chapter 3. Additionally, it provides an example of prototype testing and describes valuable insights into the dry toilet flush's performance. For these reasons, it precedes the literature review of Chapter 3.

To provide a shared testing strategy in a simple format, Chapter 3 addresses objective 2.a) and reviews the literature on various aspects of prototype testing and incorporates these aspects into a visual representation of prototype tests throughout the PD process. However, this visualisation, while potentially useful as a tool for communication and planning of prototype tests for the NMT, does not provide sufficiently general guidance for other types of PD projects. Generalisation and improvement of the tool is attempted in Chapter 5. This chapter (3) has been published as a peer-reviewed article on the *Gates Open Research* platform.

During the field testing described in Chapter 2, observations were made that cast doubt on the ability to separate solids from liquids within the NMT by settling alone. In Chapter 4, the settling and displacement processes in the NMT's collection tank are investigated thoroughly to provide qualitative and quantitative data about the operation of the tank to provide solid-liquid separation. Even though the testing visualisation presented in Chapter 3 was not explicitly used in planning these tests, it helped the researcher focus the testing efforts and develop a bespoke prototype. This chapter addresses objectives 1.a) and 1.b) and is currently being prepared for submission to a peer-reviewed Journal.

Chapter 5 was developed in parallel to Chapter 4, which means it does not build on the findings of Chapter 4 (Figure 1-2). It addresses objective 2.b) and reports on a qualitative study in which experts in the field of prototype testing in product development are interviewed. Based on their expert knowledge, an understanding of important aspects and problems of planning and conducting prototype tests is developed, and the testing visualisation developed in Chapter 3 is validated and converted into a modular tool for general use in PD. This chapter is currently being prepared for submission to a peer-reviewed Journal.

The final chapter (Chapter 6) discusses the knowledge generated in Chapters 2, 3, 4, and 5 towards its meaning for the thesis and provides concluding remarks.

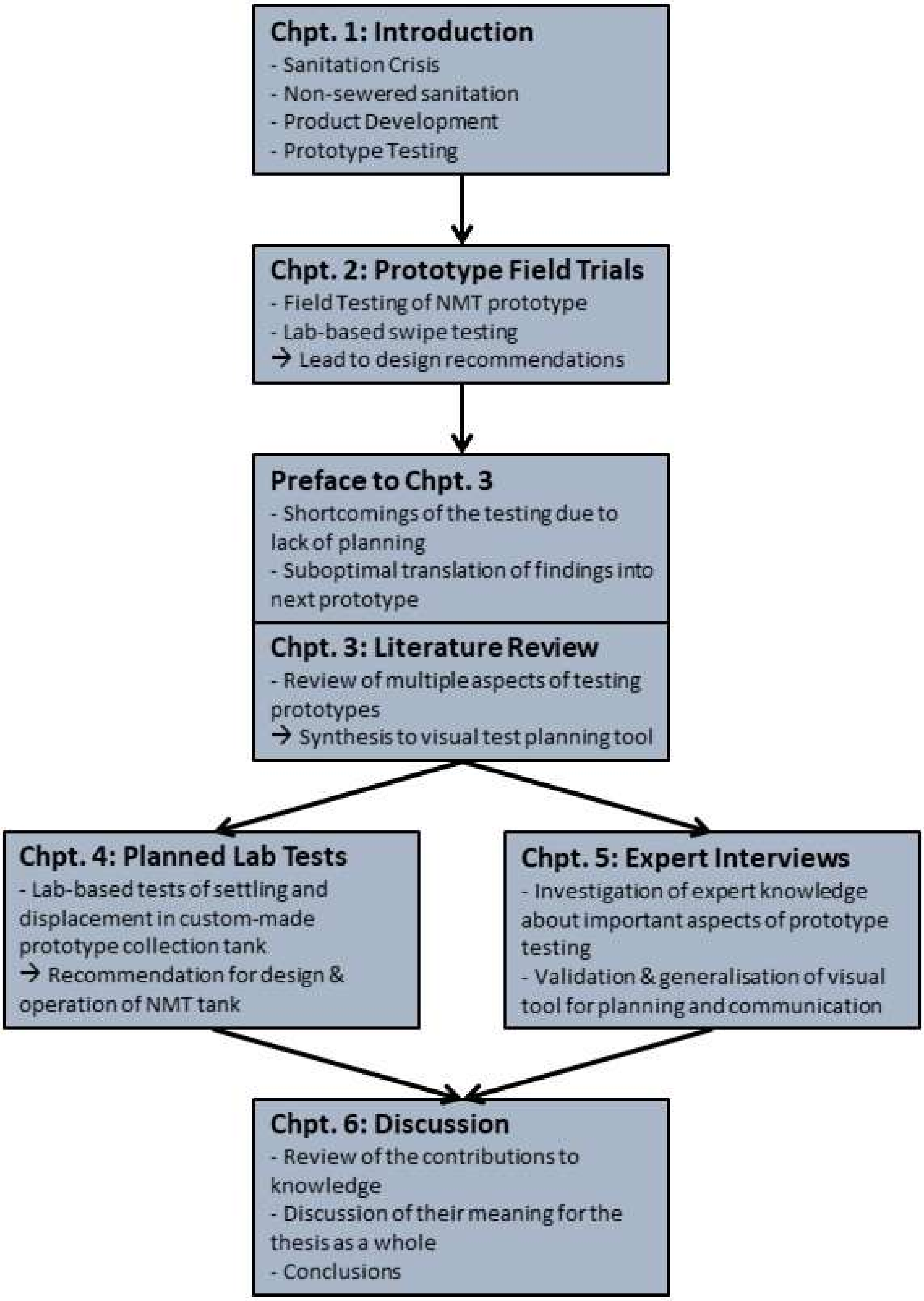

Figure 1-2: Visual representation of the thesis outline. Chapters 4 and 5 were written in parallel, which means that Chapter 5 builds on Chapter 3, but not on Chapter 4.

1.5 Co-Authors' contributions

The NMT project is a large project with dozens of members. It is thus unavoidable that any publication about the project involved multiple collaborators. The following chapters, Chapters 2, 3, 4, and 5, are all credited to several co-authors beside the first author, Jan Hennigs. Listed below in Table 1-1 in alphabetical order are all co-authors, including Mr. Hennigs, and their contributions for each chapter.

Table 1-1: Contributions of co-authors to Chapters 2-5.

Co-author	Chapter 2	Chapter 3	Chapter 4	Chapter 5
Barrington	Coordinated field trials during the planning phase	No contribution	No contribution	No contribution
Blose	Assisted with/ independently carried out data collection during field trials	No contribution	No contribution	No contribution
Collins	Co-Investigator for Design of NMT project, developed the prototype for field trials	Co-Investigator for Design of NMT project	Co-Investigator for Design of NMT project	Co-Investigator for Design of NMT project
Engineer	Developed and built prototype, coordinated and conducted set-up of testing rigs in South Africa	No contribution	No contribution	No contribution

Co-author	Chapter 2	Chapter 3	Chapter 4	Chapter 5
Finkbeiner	No contribution	No contribution	No contribution	Assisted in data collection during tool-validation
Hennigs	Developed test procedures and schedules, built prototype, set up testing rigs, carried out testing at UKZN, in households, and in laboratories, conducted data analysis, wrote the chapter	Conducted literature review, developed testing flow chart, wrote the chapter	Developed experimental design, cooperated in prototype development, carried out experiments, data collection and analysis, wrote the chapter	Developed interview questions, identified and approached interviewees, conducted interviews, transcription and analysis, developed the modular testing tool, wrote the chapter
Jiang	No contribution	Co-Investigator for Energy of NMT project	Co-Investigator for Energy of NMT project	Co-Investigator for Energy of NMT project
Kolios	Co-Investigator for Energy of NMT project	Co-Investigator for Energy of NMT project	Co-Investigator for Energy of NMT project	Co-Investigator for Energy of NMT project

Co-author	Chapter 2	Chapter 3	Chapter 4	Chapter 5
McAdam	Co-Investigator for Membrane Treatment of NMT project	Co-Investigator for Membrane Treatment of NMT project	Co-Investigator for Membrane Treatment of NMT project, consulted in the development of the prototype tank and experimental design	Co-Investigator for Membrane Treatment of NMT project
Mercer	No contribution	No contribution	No contribution	Assisted in data collection during tool-validation
Parker	Co-Investigator for Communications of NMT project, supervised student, provided guidance on structure and content of chapter	Co-Investigator for Communications of NMT project, supervised student, provided guidance on structure and content of chapter	Co-Investigator for Communications of NMT project, supervised student, provided guidance on structure and content of chapter	Co-Investigator for Communications of NMT project, supervised student, provided guidance on structure and content of chapter, assisted in contacting interviewees
Ravndal	Independently carried out data collection	No contribution	Consulted in experimental design and prototype development	Assisted in study design and data collection for tool-validation

Co-author	Chapter 2	Chapter 3	Chapter 4	Chapter 5
Sindall	Coordinated field trials on site, assisted in data collection	No contribution	No contribution	No contribution
Toolaram	Assisted in data analysis of user interviews	No contribution	No contribution	No contribution
Tyrrel	Principle Investigator of NMT project, primary supervisor, provided guidance on structure and content of chapter	Principle Investigator of NMT project, primary supervisor, provided guidance on structure and content of chapter	Principle Investigator of NMT project, primary supervisor, provided guidance on structure and content of chapter	Principle Investigator of NMT project, primary supervisor, provided guidance on structure and content of chapter
Williams	Co-Investigator for Design of NMT project	Co-Investigator for Design of NMT project	Co-Investigator for Design of NMT project	Co-Investigator for Design of NMT project

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2 Field testing of a prototype mechanical dry toilet flush

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2.1 Abstract

A prototype of a non-fluid based mechanical toilet flush was tested in a semi-public, institutional setting and in selected peri-urban households in eThekwini municipality, Republic of South Africa. The mechanism's functionality and users' perception of the flush were assessed. User perception varied depending on background: Users accustomed to porcelain water flush toilets were open to, yet reserved about the idea of using a waterless flush in their homes. Those who commonly use Urine Diversion Dehydration Toilets were far more receptive. The user-centred field trials were complemented by a controlled laboratory experiment, using synthetic urine, -faeces, and -menstrual blood, to systematically assess the efficiency of three swipe materials to clean the rotating bowl of the flush. A silicone rubber with oil-bleed-effect was found to be the best performing material for the swipe. Lubrication of the bowl prior to use further reduced fouling. A mechanical waterless flush that does not require consumables, like plastic wrappers, is a novelty and could – implemented in existing dry toilet systems – improve acceptance and thus the success of waterless sanitation.

Keywords: *WASH, Reinvent The Toilet Challenge, Iterative Design, User Testing, Science-Design Interface*

Abbreviations: BSC – Bristol Stool Chart; NMT – Nano Membrane Toilet; PRG – Pollution Research Group; SMF – Synthetic Menstrual Fluid; SOB – Silicone Rubber with Oil-Bleed effect; SU – Synthetic Urine; UDDT – Urine Diversion Dehydration Toilet; UKZN – University of KwaZulu-Natal; USFDA – United States Food and Drug Administration; VIP – Ventilated Improved Pit Latrine

2.2 Introduction

4.5 billion people worldwide lacked access to safely managed sanitation in 2015, of which 892 million practiced open defecation. Safely managed sanitation is defined as "an improved sanitation facility that is not shared with other households, and where excreta are disposed of in situ or transported and treated off-site" (WHO and UNICEF, 2017). The entailing problems, such as groundwater pollution (Graham and Polizzotto, 2013), the transfer of pathogens and the resulting diseases (Curtis, Cairncross and Yonli, 2000; Wolf *et al.*, 2014), children (especially girls) missing school (Sclar *et al.*, 2017), and increased risk of assault and rape, mainly for women when they have to urinate/defecate in the open (Jadhav, Weitzman and Smith-Greenaway, 2016; Miiro *et al.*, 2018), are all serious inhibitors of human development (Jahan, 2016).

Providing sanitation for low income- and informal settlements in fast-growing cities of the Global South poses particular challenges: while the population in these areas is increasing, access to piped water and sewers is often limited (Parnell, Simon and Vogel, 2007; Cobbinah and Poku-Boansi, 2018). Pit latrines and Urine Diversion Dehydration Toilets (UDDT) are common waterless sanitation solutions (Semiyaga *et al.*, 2015). However, their pedestals (where present) can be considered uncomfortable, prone to fouling and malodour, and sometimes dangerous for children to use, as they can fall into the pit (Roma *et al.*, 2013; Mkhize *et al.*, 2017). This is a considerable obstacle for the acceptance of waterless sanitation technologies: if users prefer defecating in the open to using dry toilets, the provision of these toilets has little impact.

A solution could be a waterless toilet flush. Such a flush, as 'user interface', would be the physical barrier between the user and the faecal material inside the toilet, and thus have the potential to resolve problems of odour, of unpleasant visual contact with faeces and fouling, and of the danger of children falling into the pit. There currently are marketed applications of dry toilet flushes which seal the faeces in consumable materials, like the Dry Flush©, designed for camper vans or cottages not connected to sewers (Livingston and Roczynski, 2014) or the Loowatt toilet, already in use at British music festivals and in Madagascar (Natt *et al.*, 2011), and technologies using small amounts of water, for example vacuum toilets (Wendland *et al.*, 2007), or so-called microflush toilets (e.g. Mecca, Davis and Davis, 2013). There are also attempts to reduce water usage by reusing grey wastewater for toilet flushing (Garzon and Paterlini, 2018).

However, all of these technologies have problems with applicability to common dry toilet technologies used in cities of the global south: They either rely on at least some infrastructure for water, electricity, or both, or rely on specific consumables, such as plastic wrappers to contain the faeces. There currently are no published patents or research articles on purely mechanical, non-fluid based flush systems. This may be because a mechanical flush requires further storage or treatment of excreta on site, whereas water allows transport of the faecal material to a centralised treatment facility. Secondly, the development of a waterless flush is a challenging task, as faeces can be highly adhesive to various surfaces (Rose *et al.*, 2015). Nonetheless, compared to alternative technologies, such a flush would have the environmental advantage that it does not consume water, electricity, or material in which to wrap the faeces. From a technical perspective, a mechanical flush is advantageous as it operates independently of outside infrastructure, like water or electricity. Its only requirement would be the manual operation by the toilet user, which would make its operational cost negligible, giving it yet another advantage over other available toilet flushes.

Another factor to consider is a flush’s ability to convey solid waste, e.g. menstrual absorbents. While the disposal of solid waste into pit latrines and other sanitation systems is detrimental to transport and treatment of the faecal sludge, and is therefore discouraged, it frequently happens nonetheless. The reasons for this vary, but the lack of alternative solid waste disposal options and the stigma surrounding menstrual hygiene are two common examples (Radford *et al.*, 2015;

Tembo, Nyirenda and Nyambe, 2017). A flush should not necessarily accommodate this behaviour, but it is likely that menstrual absorbents are disposed regardless of user instruction. Therefore, a certain level of resilience against these unwanted inputs should be achieved.

To address these diverse challenges, based on an exploratory field study using household surveys in Kumasi, Ghana, Agile Innovation methods were employed to develop a mechanical flush which conveys faecal material from the toilet bowl and shields the users from the sight and odour of previous users' faecal matter (Tierney 2017). A prototype of this mechanical flush was built to further its development by assessing its functionality and its reception by users (Figure 2-1). Following the concept of user-centred design (Salah, Paige and Cairns, 2015), the mechanical flush has to reliably provide satisfactory service, be perceived as clean, easy to use, and desirable, if it is to be successful.

Field trials are indispensable for the testing of prototypes in real-life scenarios (Ulrich and Eppinger, 2016) and in the spirit of Agile Innovation, prototypes should be tested on the product's target audience as soon as possible (Beaumont *et al.*, 2017). However, the variability of frequency of toilet use and consistency of faeces (Rose *et al.*, 2015) in authentic use conditions lead to a low level of control for the purpose of scientific performance evaluation. A trial large enough to eliminate these concerns would be prohibitively expensive. Therefore, the development of this novel technology will inevitably require controlled experiments to complement the findings from field tests. Both types of tests, the user-centred field trials and the controlled laboratory experiments, deliver valuable insights into the prototype's strengths and weaknesses. In combination, these findings are transferred into design recommendations, which form the basis for the next cycle of the iterative design process (Bresciani, 2015).

In exploration of the interface between design-based prototyping techniques and controlled experimental research, this paper presents the results of user-centred field testing and experimental evaluation of a mechanical toilet flush, which will inform the next design-iteration regarding user acceptance and swipe efficiency.

2.3 Methodology

2.3.1 Prototype description

The test object was a prototype pedestal incorporating the mechanical flush system, which is activated by moving the toilet’s lid. Gears connect the lid to a rotating bowl that turns downward as the lid is closed. A swipe situated inside the pedestal is connected to the bowl-lid-gear-system. As the bowl rotates, the swipe moves downward, clearing remaining faeces out of the bowl. This mechanism acts as a barrier for visual and olfactory irritation of the user. Figure 2-1 shows a cross section of the mechanical flush, with the rotating bowl and the swipe highlighted in blue and orange. The material used for the body of the prototype was polyurethane (*ALCHEMIX® VC 3341;* Alchemie Ltd, Warwick, England), a plastic often used in temporary sanitation systems, i.e. chemical toilets. A smooth, white surface finish resulted in an appearance similar to that of a porcelain water flush toilet, as can be seen in Figure 2-2.

2.3.2 Study area

The inhabitants of eThekwini municipality, Republic of South Africa, represent a potential target customer group, as its peri-urban population is to a great extent not currently connected to sewered sanitation: in 2016/17, the municipality with a population of 3,820,174 provided 247,079 households with access to free basic level sanitation services, through UDDTs, existing ventilated improved pit latrines (VIP), or ablution blocks (eThekwini Municipality, 2017).

Hence, the prototype was tested in field trials in eThekwini. Firstly, one prototype unit was installed at the University of KwaZulu-Natal (UKZN) where it was situated in a designated toilet room adjacent to the laboratory facilities of the Pollution Research Group (PRG), and used by staff, students, and visitors for a total of 8 weeks. Figure 2-2 a) shows the prototype in the toilet room, and Figure 2-2 b) a schematic of the installation. Here, the unit was connected to a sewer pipe, which was flushed through with water on a regular basis to prevent a blockage of dry material.

Following the first month of testing at UKZN, two prototype pedestals (identical to the first) were successively tested in UDDT outhouses of six households in a low income community in a peri-urban region of the eThekwini municipality. The municipality supplies the water and sanitation services to the households, including construction, emptying, and maintenance of the UDDT facilities. Each household is supplied with 200 L of water per day, via a standpipe with a water restrictor, making water a limited resource too valuable to use for toilet flushing. The municipality, UKZN researchers and staff of Khanyisa Projects jointly identified households suitable and willing to participate in the study. Suitability was assessed on accessibility of the household, number of users of the toilet, and condition of the existing outhouse and pedestal. The prototypes replaced the UDDT-pedestals and flushed directly into the faecal sludge vaults underneath. At each household, the unit remained installed for one month.

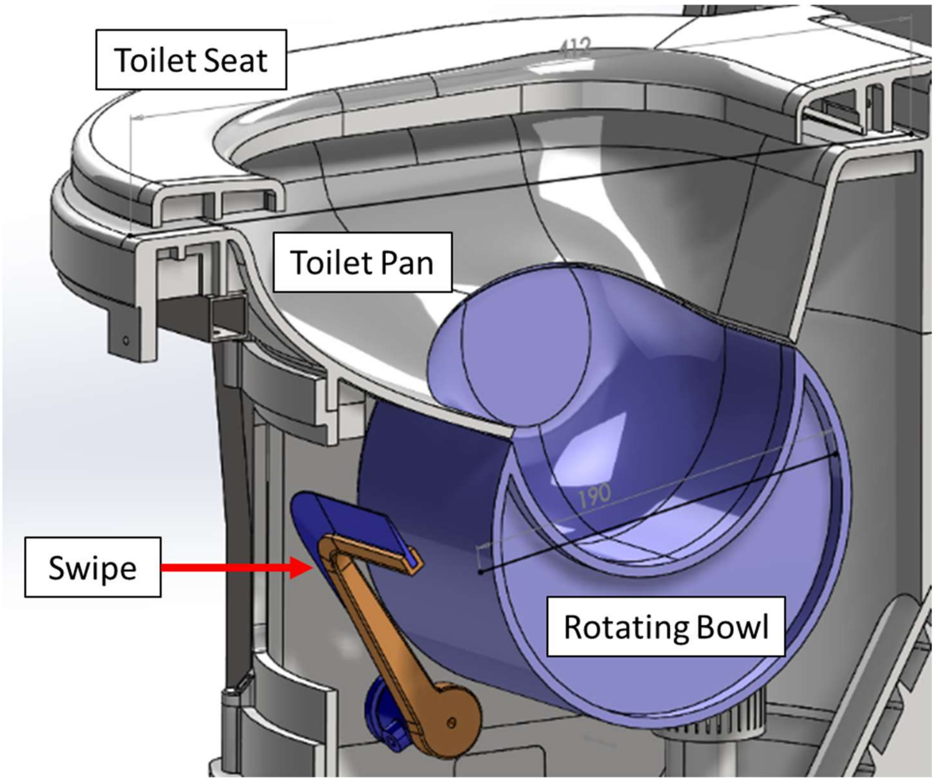

Figure 2-1: Cross section showing the rotating bowl and swipe – through gears connected to the toilet lid, the bowl rotates downward (from this perspective: counter-clockwise), and the swipe moves in concert to clean the bowl's surface.

2.3.3 Preliminary testing in a semi-public institutional setting at UKZN

Testing in an institutional setting at UKZN was considered the first real-use trial for the prototype, before it could be installed in households. Most importantly, the proper functionality of the flush had to be ensured, as the prototype would replace the households' only toilet pedestal. While the original pedestal remained with the families to be re-installed after the trial period, and in case the prototype malfunctioned, this would be an undesirable event for the families and was to be avoided.

2.3.4 Functionality Tests

Based on its surface energy, Tierney (2017) identified silicone rubber as favourable material for the swipe and bowl-surface to maximise cleaning efficiency while reducing friction. He also assumed that a lubricated surface would be less prone to fouling than a dry surface, and proposed a surfactant solution for this aim. Based on these recommendations, and on availability in the manufacturing process, three different materials for the swipe were tested consecutively, namely *Poly PT Flex* **Polyurethane Rubber** (Polytek Development Corp., Easton, PA, USA), *Essil 291/292* **Silicone Rubber**, and *Essil 291/292* **Silicone Rubber with oil-bleed-effect (SOB),** with the oil-bleed-effect creating a constant lubrication of the swipe's surface (Both Axson Technologies, Saint-Ouen-l'Aumône, France) (Table 2-1).

The prototype production conditions required the rotating bowl to be of the same material as the pedestal itself (*ALCHEMIX® VC 3341 polyurethane)*, which could not be alternated during the trials. Hence, to compare lubrication of the bowl's surface prior to use to the unlubricated surface, a pump-action spray bottle (as commonly used for disinfectant in laboratories and household toilets) filled with a solution of 10 g/L liquid hand soap in tap water was placed next to the pedestal and labelled "please give two sprays into the bowl before using the toilet" on 54% of trial days (Table 2-1). Thus, about 2 mL of soapy water were dispersed into the bowl before use of the toilet. To prevent users from cleaning fouling out of the bowl manually, no toilet brush or other cleaning equipment was supplied in the toilet room.

Table 2-1: Flush testing schedule at UKZN (Test days are not counting weekends)

Swipe material	Polyurethane		Silicone		SOB	
Number of Test Days	6	7	6	7	6	7
Spray lubrication	no	yes	no	yes	no	yes

The data collected on swipe functionality were:

- Written observations about the handling and functionality of the prototype in a daily diary
- Photographs of the toilet bowl (daily) and the rubber swipes (upon removal)

As the input of faeces throughout a given day could not be determined, the effectiveness of the swipe was measured on a polar scale only, i.e. whether the photograph of the toilet bowl at the end of the day showed a clean bowl or not. After the daily photograph was taken, the bowl was cleaned.

Figure 2-2: a) prototype pedestal with mechanical waterless flush, installed in a dedicated toilet room adjacent to the laboratories of the Pollution Research Group at the University of KwaZulu-Natal; b) schematic of the installation: The pedestal is connected to the sewer mains and has a ventilation pipe from inside the unit. The gear system is shown to be on the side of the pedestal, underneath the cover

2.3.5 Surveys and Interviews

Surveys and interviews captured details of users' experience of, and attitude towards, using the prototype:

Short survey questionnaires were provided in the toilet room, and users were asked to fill one out every time they entered, even when they then decided against using the toilet. The intention was to gather information on the users' perception of the prototype's cleanliness, odour, ease of use and how they compared it to their usual toilet. A copy of the questionnaire used can be found in the Appendix (Section 2.9).

Eight of the users agreed to participate in semi-structured interviews about their experience using the toilet and their attitude towards it. The topics covered in the interview are listed in the Appendix (Section 2.9). All of the interviewees were either members of the PRG at UKZN or affiliated with it through their work, and so are well acquainted with sanitation research.

The interviews were conducted in English, recorded and transcribed. The transcripts were then coded to identify recurring themes of observations and attitudes of the users, as described by Weston *et al.* (2001).

Both the questionnaire and the interview topics were developed by the interdisciplinary author team of social scientists, designers and engineers. They were designed to gather information on the user experience in relation to the prototype, particularly those components which could be re-designed if users were dissatisfied. The questionnaire was reviewed by a social scientist of UKZNs School of Built Environment Development Studies who has experience working with communities in the peri-urban settlements of Durban, who confirmed that the questions being posed were both clear and culturally appropriate. The interview topics were reviewed by a Team Leader within PRG at UKZN who confirmed that members of the Pollution Research Group would understand and be open to answering them.

To further ensure that they were understood correctly, the questionnaires were publicly presented at the PRG offices at the beginning of the study and discussed informally during the trials. The interviews were held in a semi-structured manner specifically to ensure that the questions were understood correctly and that answers provided the information we needed.

2.3.6 Household Tests

By replacing the UDDT pedestal, the prototype became the only available toilet for the household and was thus used by all members of the household. Detailed instructions were provided by UKZN researchers and a representative of eThekwini municipality in person, and printed user instructions were also posted on the inside of the outhouse doors in isiZulu, the participants’ native language. The families were provided cleaning equipment and asked to clean the prototype as they saw fit, but to use as little water as possible. Part of the instruction was to not use water when flushing the toilet.

After the initial tests at UKZN, the SOB swipe was considered to be the most promising with regard to cleaning effectiveness and resistance to fouling. Therefore, swipes of this material were used in the household units throughout the trials.

Analogous to the test at UKZN, the data collected during visits twice a week were:

- Written observations of the mechanism's functionality
- Photographs of the bowl's cleanliness
- Survey questionnaires in isiZulu

2.3.7 Swipe Test in the Laboratory

To further compare the three swipe materials: polyurethane, silicone, and SOB, they were tested in controlled laboratory experiments using:

- Simulant faeces in three consistencies, simulating solid, soft glutinous, and liquid faeces (type 3-4, 5-6, and 7 on the Bristol Stool Scale (BSC), respectively (Lewis and Heaton, 1997), see Appendix (Section 2.9))
- Synthetic urine as a secondary lubricant for the toilet bowl
- Toilet paper
- Tampons saturated with synthetic menstrual fluid
- The influence of lubricating the bowl's surface was tested by spraying a solution of 10 g/L liquid hand soap in tap water into the bowl before adding the simulant loads

A modified version of the mechanical flush prototype was used, which included the toilet lid, -seat, and flush mechanism, but had no connection to a sewer or faecal sludge vault. Instead, the simulant loads were flushed directly into a bucket underneath the rotating bowl. Photographs of the inside of the bowl were taken a) beforehand, b) after dropping in the simulant load, and c) after flushing the simulant load. This methodology was based on tests used during the development of the mechanical flush (Tierney, 2017).

Using *ImageJ* software (FIJI-distribution, ImageJ development team at LOCI, University of Wisconsin-Madison) (Schindelin *et al.*, 2012, 2015; Schneider, Rasband and Eliceiri, 2012), the fouled area relative to the area of the rotating bowl was determined before and after flushing (Figure 2-3). Thus, a fouling-removal rate could be calculated:

$$\textbf{removal rate} = 1 - \frac{\left(\frac{A_{covered}}{A_{bowl}}\right)_{After\ Flush}}{\left(\frac{A_{covered}}{A_{bowl}}\right)_{Before\ Flush}} \qquad \textbf{(2-1)}$$

Where $A_{covered}$ is the area covered with faeces and A_{bowl} is the area of the bowl. Both were measured in pixels. Tests were conducted in triplicate.

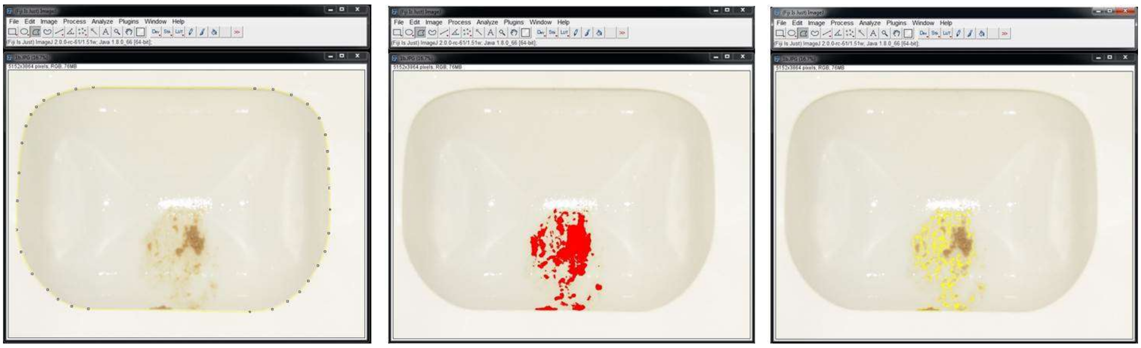

Figure 2-3: Image analysis using ImageJ software: a) with the polygon selection tool, the total area of the bowl is measured; b) with the color threshold tool, the fouled area was identified; c) shows the selection of the fouled area.

2.3.7.1 Simulant loads

For **synthetic faeces**, an adapted formula of the recipe proposed by Penn *et al.* (2018) was used. The recipe can be found in the Appendix (Section 2.9). Water content of 40%, 60% and 90% was used to simulate solid faeces of type 3-4, soft-glutinous faeces of type 5-6, and liquid faeces of type 7 on the BSC respectively. Harder faeces (types 1 and 2 on BSC) were not simulated, as the solid faeces already left no visible fouling.

Urine was simulated using an isotonic NaCl-solution (9 g_{NaCl}/L) with 3 drops/L green food dye ("Extra Strong Green Food Colour Geld", Dr Oetker UK Ltd., United Kingdom) in deionised water.

There is very little literature on **Synthetic Menstrual Fluid** (SMF), with the exception of medical research, e.g. (Christiaens, Sixma and Haspels, 1981; Dasharathy *et al.*, 2012; Yang *et al.*, 2012), nor are there many publications on the rheology or staining properties of real menstrual blood, which can partially be explained by its great variability in many parameters throughout the days of menstruation (Beller, 1971; Beller and Schweppe, 1979; Levin and Wagner, 1986), and partially by the apparent societal taboo to investigate or even talk about menstruation (Hertz, 2018; Spadaro, d'Elia and Mosso, 2018; Wilson *et al.*, 2018). In the tampon industry, the *syngina test* measures a tampon's absorbency (EDANA, 2015), in which *syngina fluid* is used. However, it has very little to do with the texture of actual menstrual fluid, but rather has a similar formula to the synthetic urine used in this study: The US-American Food and Drug Administration (USFDA), as well as the European Disposables and Nonwovens Association (EDANA), dictate the formula as "10 grams sodium chloride, 0.5 gram Certified Reagent Acid Fuchsin, 1,000 milliliters distilled water" (USFDA, 2010). Former member of the "tampon task force" (Vostral, 2017), Nancy Reame, cites an older FDA-recipe for syngina-fluid, pre-dating the standardisation of the syngina test, that seems to attempt to simulate a more realistic rheology of menstrual fluid: 10 g NaCl, 4 g $NaHCO_3$, 4 g cellulose gum, 100 g glycerol, 880 g water, trace of food colouring (Marlowe, Weigle and Stauffenberg, 1981 in: Reame, 1983). But while this liquid is thicker than the modern "syngina fluid", it seems to have quite high surface tension and leaves no stains on the smooth, solid surface of the polyurethane toilet bowl tested for this study. From experience of the authors, real menstrual fluid is known to leave blood stains on porcelain toilet bowls, so this older formula could not be used either.

Instead, after some experimentation, a mixture of 40% defibrinated horse blood (TCS Biosciences Ltd., Botolph Claydon, United Kingdom), 10% glycerol (Mystic Moments UK, Fordingbridge, United Kingdom), and 50% isotonic NaCl-solution was prepared. An informal panel of colleagues who menstruate agreed that its viscosity, colour, and staining properties sufficiently resembled those of real menstrual fluid. Medium absorbency tampons (Tampax® brand, Procter & Gamble, Weybridge United Kingdom) were fully saturated in this liquid, and then dropped into the toilet bowl from seat-level. This left a spatter pattern in the bowl. While tampons are far from being the most commonly used menstrual products in eThekwini municipality (Beksinska *et al.*, 2015), and flushing of tampons, like other solid waste, should be discouraged for most sanitation systems, the method described above provided a useful way to administer blood stains to the toilet bowl as well as a test as to whether the mechanism could – in theory – handle flushing a tampon. Similarly, the flushing of menstrual pads was tested successfully, but this provided no useful staining of the toilet bowl and was thus not investigated further.

2.3.8 Ethics Statement

The methodologies used for this study were approved by the Cranfield University Research Ethics Committee (all parts of the study, CURES approval numbers 3512, 3513, and 4534 for field work; 4750 for laboratory tests), and the Biomedical Research Ethics Committee at UKZN (the part of the study conducted in South Africa, i.e. the field testing, Approval Number BE409/17). Written, informed consent was obtained from all participants in either English or isiZulu, whereby the supplied information sheets emphasized the voluntary nature of participation and the option to leave the study at any time or opt out of answering any questions.

2.4 Results

2.4.1 Tests at UKZN

Use of the prototype toilet

171 visits to the toilet room were recorded by means of collected survey sheets. Out of those, 167 times the user decided to use the toilet. The users were mostly staff of the PRG laboratories, several of whom used the prototype multiple times. Therefore, the number of individual users was likely much smaller than the recorded number of visits. As can be seen in Table 2-2, it was used by female and male participants alike, for urination as well as defecation. The question on the type of use (urination and/or defecation) was only introduced to the survey

sheets after an initial testing period, hence the smaller usage population. On weekends, the facilities remained closed.

Table 2-2: User Statistics of trial at UKZN.

Recorded Visits to Prototype (by means of collected surveys)	171
Visits on which the user specified they used the Prototype	167 (97.7%)
Male uses	84 (49.1%)
Female uses	85 (49.7%)
User specified their gender as 'other'	1 (0.6%)
User did prefer not to specify their gender	1 (0.6%)
User specified they only urinated (out of 108 surveys including this question)	63 (58.3%)
User specified they only defecated or defecated and urinated (out of 108 surveys including this question)	44 (40.7%)

Swipe material comparison

As can be seen in Table 2-3, out of total days tested (d_{total}), the toilet bowl was observed clean at the end of the day (d_{clean}) more often than not, and without lubrication, the SOB swipe exhibited better performance than the other two materials. Lubrication prior to use improved all swipes' performance, and both silicone swipes performed better than the polyurethane swipe. In total, the bowl was observed to be clean at the end of 30 out of 39 days (77%).

Table 2-3: Days on which the toilet bowl was found clean at the end of the day.

	Polyurethane Swipe (d_{clean}/d_{total})	Silicone Swipe (d_{clean}/d_{total})	SOB Swipe (d_{clean}/d_{total})
No lubrication	**4/6 (67%)**	**4/6 (67%)**	**5/6 (83%)**
With spray lubrication	**5/7 (71%)**	**6/7 (86%)**	**6/7 (86%)**

User surveys

Since some users used the toilet multiple times, they also completed multiple questionnaires. With this pseudo replication, and with a relatively small population size, statistical analysis, e.g. on the impact of gender on a certain user response, was deemed inappropriate. However, the collected answers, (Table 2-4), can give an indication of the users' likes and dislikes. A three-point Likert-type scale using stylised smiling-, neutral-, and frowning faces was used to represent a positive-, neutral- or undecided-, and negative response, respectively.

a) Odour: The majority of surveys reported no negative odour. It should be noted that in the laboratories outside the toilet test room, analyses of faecal samples were conducted on most days, and this may have influenced the users' ability to detect odour changes inside the toilet room.
b) Cleanliness: Two thirds of user responses reported a clean toilet, while the remaining replies were evenly split between reporting a dirty toilet and an undecided reply.
c) Ease of use: the clearest result was achieved for the question on ease of use, where 87% of submitted responses considered the prototype easy to use and only 2% replied that it was not. It should be noted that the

perception of ease of use likely changed over time as participants used the toilet multiple times and became acquainted with it.

d) Toilet preference: The only question that had the highest percentage of replies as "neutral" (68%) was on toilet preference. Of the remaining replies, three times more said to prefer the prototype toilet (24%) than their own (8%).

Table 2-4: User survey responses.

How much do you agree with the statement…	Positive replies	Neutral replies	Negative replies
… "*The toilet didn't smell bad*"? (n=171 responses)	**120 (70%)**	**13 (8%)**	**38 (22%)**
… "*The toilet was clean*"? (n=171 responses)	**113 (66%)**	**29 (17%)**	**29 (17%)**
… "*The toilet was easy to use*"? (n=169 responses)	**147 (87%)**	**19 (11%)**	**3 (2%)**
… "*I prefer using this toilet to my usual toilet*"? (n=170 responses)	**40 (24%)**	**116 (68%)**	**14 (8%)**

Interviews

Eight users were interviewed about their experience with and attitude toward the prototype. There were four male and four female interviewees, none had a gender expression different from their sex; four were in the age group 30-40 years, three

20-30 years, and one 60-70 years. While the interviewees were from diverse age groups and nationalities, they all had an academic background in sanitation research, and were all accustomed to water flush toilets at home as well as at work.

Most aspects about which interviewees were questioned yielded both positive and negative views (Figure 2-4):

Only the four women, believed to be the four interviewees having first-hand experience with menstruation, were questioned about their attitude towards the prototype with regard to menstrual hygiene. All said that they would not mind flushing menstrual absorbents into the toilet if they were permitted to do so. On the other hand, they acknowledged that cleaning menstrual fluid out of the bowl could prove difficult and that blood stains would be of particular concern (compared to faeces). While this was their main concern about using the prototype for menstrual hygiene, they also mentioned the lack of a bin in the toilet room as a barrier.

While some interviewees voiced uncertainty about how the flush mechanism works, a majority said that they had no physical difficulties using the prototype, and that its use was easy to understand. None of them said they had any cultural or religious problems using the prototype: seven out of eight thought if they were to install it in their homes, they would install it in their usual toilet's location, which in the case of all interviewees was inside the house.

All interviewees agreed that they would have liked cleaning equipment to be supplied in the toilet room, or that it would be necessary if they used this pedestal in their homes. Most interviewees mentioned that they thought cleaning would have to be more frequent than, or at least different to, that of a water flush toilet. However, half of the interviewees mentioned that they did not consider cleaning the waterless toilet would be any more difficult or unpleasant than cleaning a water flush toilet.

In six interviews, there was a mention of negative odour being detected at some point during the trial period, but half of all interviewees reported that odour was either neutral or at least tolerable, meaning that odour levels were not exceeding those of a water flush toilet in a similar institutional setting. Two users claimed to have noticed a positive smell (“It smells nice”).

The importance of saving water was discussed in six interviews, and this was the only aspect that was not seen as problematic by any of the interviewees. However, only one interviewee explicitly mentioned they would not mind changing their behaviour for the sake of water preservation.

The novel, clean, design, similar to that of a porcelain toilet was praised, but there was also criticism of the small size and depth of the entire toilet pan, as users disliked the proximity to the excreta.

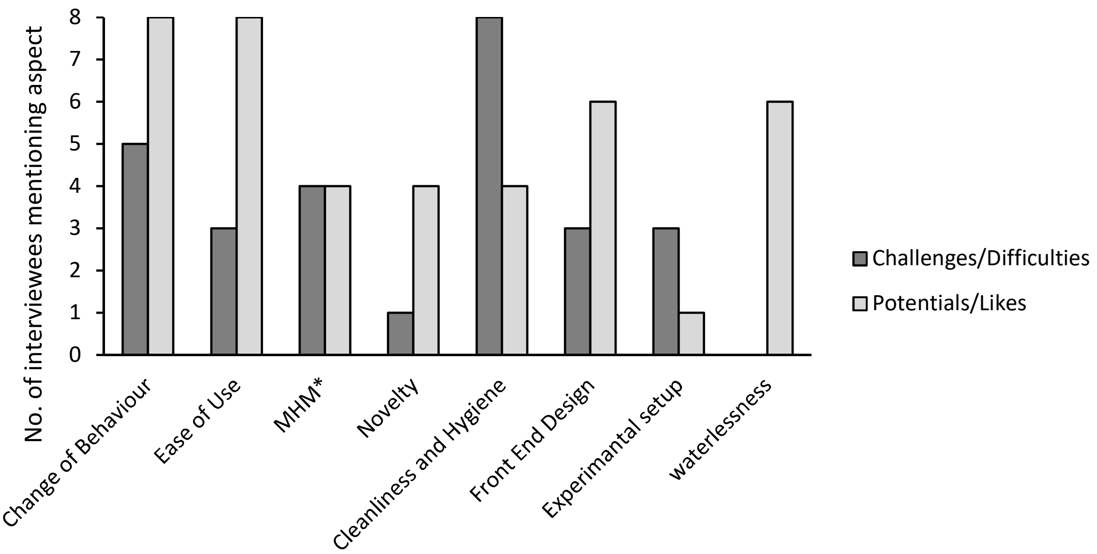

Figure 2-4: Potential vs Challenges as seen by the 8 interviewees at UKZN. *MHM: Menstrual Hygiene Management – only the four female interviewees were questioned about this aspect.

Additional observations

During the trials, some unexpected issues with the prototype design were discovered. One complaint that was raised by several users, both in person as well as in handwritten comments on the survey sheets, was that they had to aim throwing the toilet paper into the opening of the rotating bowl. If paper fell into any other part of the pan, it would stick there on the damp surface, and the lack of flush water would mean the user would have to remove it manually. One male user complained about having physical contact with the shallow front of the toilet pan when sitting down. Many users mentioned they thought the spray bottle that was provided was helpful, and they suggested incorporating an automated spray into the system, as this could also solve the problem of toilet paper getting stuck. Another observation was a small accumulation of urine residue at the lip of the toilet pan toward the edge of the rotating bowl. This was due to the shape of the pan and should be easily remediated in an updated design.

2.4.2 Household Tests

User perception

The two household prototypes were tested in parallel, in three sets of two households. They were well received by four households (HH 1,2,5, and 6 in Table 2-5 and Figure 2-5), whereas the other two households (HH 3 and 4) seemed to be more critical. Most of their user survey replies were more negative or neutral than positive, as compared to households 1,2,5, and 6, whose replies were at least 77 % positive for each question (Figure 2-5). Surveys were submitted by female and male users as well as users who identified as 'other', and a small percentage of users preferred not to disclaim their gender identity (Table 2-5). Only in the first two households were surveys submitted by people who said they did not use the prototype. Surveys were completed more often by people who had defecated rather than just urinated. Not all surveys were filled out completely (Table 2-5 and Figure 2-5). Whilst households 3 and 4 communicated their reservations, a general trend of positive replies was derived from the user surveys. Of particular interest are the replies to the question about toilet preference. Even household 4, while submitting largely negative replies about their views on ease of use and cleanliness, submitted only a small percentage of replies stating they preferred their usual toilet. Due to social and language barriers as well as lack of field work experience, interviews with members of each household were conducted by social scientists of UKZN, who shared a preliminary report of their findings with the authors. However, these findings could not be reported here, as they are in preparation for publication by the researchers who conducted the interviews.

Table 2-5: Demographics of collected user survey replies.

Gender Identity:	HH1	HH2	HH3	HH4	HH5	HH6
Female (%)	48.8	38.1	46.5	28.4	61.1	50
Male (%)	44.4	54	52.2	25.3	38.9	45.5
Other (%)	0	0	0.6	45.3	0	0
Rather not say (%)	0.5	1.6	0.6	1.1	0	4.5
Left unanswered (%)	6.3	6.3	0	0	0	0
I used the toilet:						
Yes (%)	61.5	87.3	96.9	98.9	93.7	90.9
No (%)	30.2	7.9	0	0	0	0
Left unanswered (%)	8.3	4.8	3.1	1.1	6.3	9.1
I used it for:						
Urinating only (%)	34.1	22.2	27.7	0	10.5	36.4
Defecating (%)	62.4	47.6	64.2	96.8	89.5	59.1
Left unanswered (%)	3.4	30.2	8.2	3.2	0	4.5

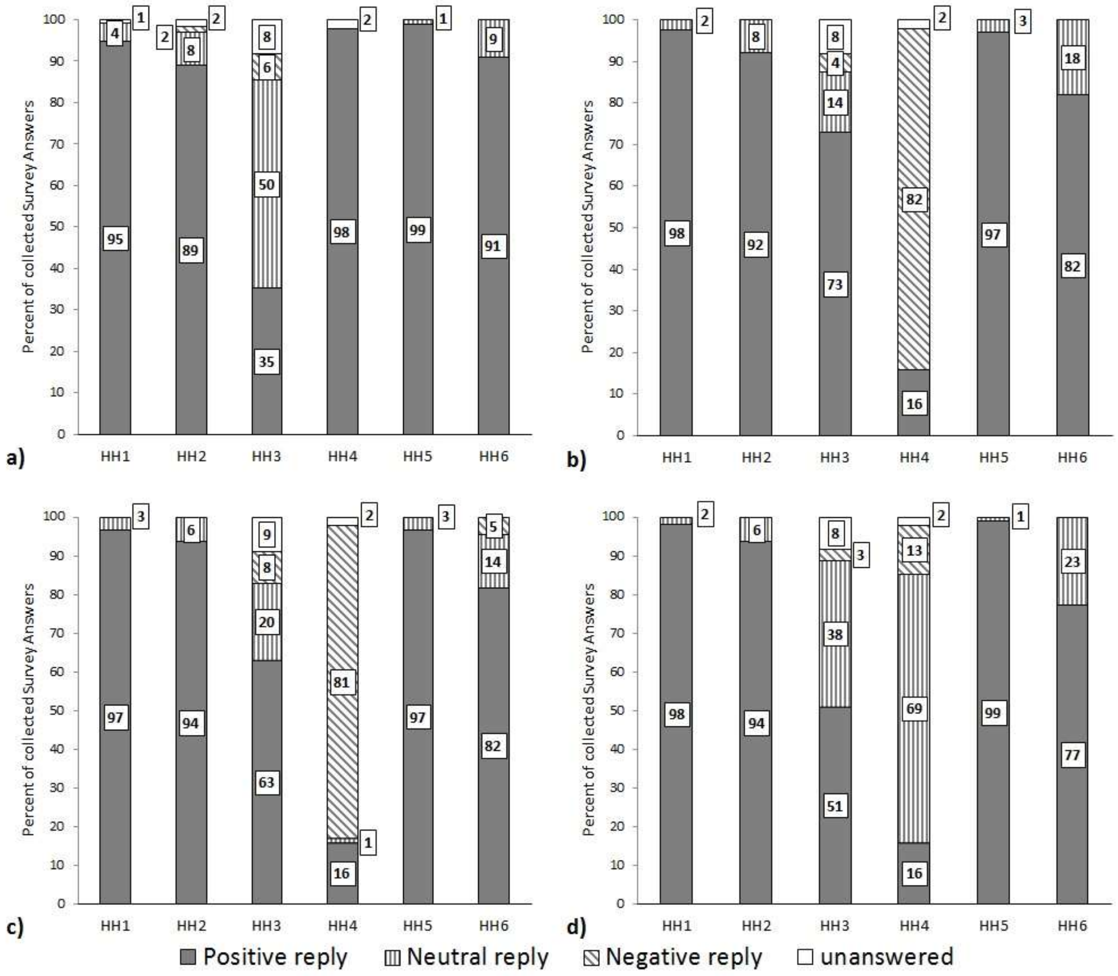

Figure 2-5: User survey replies from the households, answering the questions “How much do you agree with the statement…?” a) "…the toilet didn't smell bad", b) "…the toilet was easy to use", c) "…the toilet was clean", and d) "…I prefer this toilet to my usual one”.

Prototype performance

The mechanism in both prototype units functioned without problems in the first set of households (1 and 2) and appeared very clean at almost every visit. However, this was likely impacted because the families used water to keep the toilets clean: During visits water droplets were found on the units’ seats and bowls. This was later observed in all households.

In the second set of households, both units started exhibiting signs of fatigue: In household 3, a V-belt ruptured and had to be replaced. The bowl could be observed to have a little fouling when checked during visits. In household 4, the bowl had a failure at the connection point to the gear mechanism. The top half of the unit was replaced with the unit at UKZN, which was out of use by that time.

In the third set of households, while user surveys indicated contentment with the prototypes, water was also used to maintain a cleaner bowl. Both units were observed to have fouling in the bowl during one of the visits, showing that the performance of the swipe and flush mechanism was not always satisfactory. One of the units suffered another failure at the swipe mechanism, which was mitigated by replacing a set of screws.

In all households, blockages occurred of the prototype pedestal's outlet into the vault underneath. This led to material filling up underneath the rotating bowl and eventually impacted the prototype's cleanliness. The blockages could be cleared upon discovery, but might have impacted the users' perception of the prototype.

2.4.3 Swipe Test in the Laboratory

The removal rates as determined with Equation (2-1) for the swipe materials polyurethane, silicone, and SOB, with three different types of faeces, no lubrication, or lubrication with spray and/or synthetic urine (here: SU) are listed in Table 2-6. With solid faeces (BSC type 3-4), no significant fouling occurred with any swipe material regardless of lubrication. Soft (BSC type 5-6) and liquid (BSC type 7) faeces yielded more diverse results. The error margins indicate a large variation of results among triplicates. Negative values show that, with soft faeces and little to no lubrication, the swipes can smear the fouling over a wider area than originally fouled instead of removing it from the bowl. To compare the swipe materials, all values for the material were averaged, resulting in the last column of Table 2-6 (Average). The overall swipe efficiency of the SOB swipe material was higher than that of the silicone and polyurethane swipes. The polyurethane swipe achieved the highest removal efficiency for all types of synthetic faeces when spray lubrication and synthetic urine were added. However, without synthetic urine and/or spray, and particularly with soft faeces, the silicone and SOB swipes produce noticeably better results than polyurethane.

The tests with synthetic menstrual fluid produced no significant results. None of the swipe materials, with or without lubrication, were able to effectively remove blood stains from the rotating bowl's surface. The tampons were successfully flushed out of the bowl, but most staining remained. Therefore, the calculation of removal rates was deemed unnecessary.

Table 2-6: Removal Rates determined using ImageJ Software.

	Lubricant	**For solid faeces in %**	**For soft faeces in %**	**For liquid faeces in %**	**Average for swipe material in %**
SOB	Spray + SU	100	64 ±8	75 ±6	68 ±10
	SU	100	36 ±28	83 ±9	
	Spray	100	79 ±10	54 ±7	
	Dry	100	3 ±2	18 ±9	
Silicone	Spray + SU	100	69 ±29	89 ±5	62 ±12
	SU	100	71 ±17	73 ±13	
	Spray	100	12 ±5	25 ±1	
	Dry	100	-5 ±1	12 ±7	
Polyurethane	Spray + SU	100	92 ±6	90 ±6	50 ±17
	SU	100	0 ±45	52 ±3	
	Spray	100	-51 ±7	70 ±10	
	Dry	100	-53 ±8	1 ±7	

*Removal rates are average of triplicates; average for swipe material is from all 12 values, error margins are standard error of the mean

2.5 Discussion

The mechanical flush is part of the Nano Membrane Toilet (NMT) project at Cranfield University (Parker, 2014). The NMT is being developed as a standalone, non-sewered, household-level sanitation system that separates solid and liquid wastes (E Mercer *et al.*, 2016) and treats them in combustion (Jurado *et al.*, 2018) and membrane processes (Wang *et al.*, 2017) respectively. While a complex technological solution like the NMT could solve a variety of other issues surrounding the storage, transport and treatment of faecal sludge (Strande, 2014), the mechanical flush can be implemented independently, into already existing sanitation systems like pit latrines, chemical toilets, camping, or composting toilets. This could improve their perceived cleanliness, comfort, and hygiene, and thus their acceptance.

The flush's effectiveness in removing faecal matter from the bowl was demonstrated, and the laboratory tests confirmed the preliminary findings regarding the efficiency of swipe materials and use of a lubricating spray. The SOB swipe was least susceptible to fouling, likely due to the oil bleed effect reducing the adhesion of faeces. It also had the best overall removal efficiency, which corresponds to Tierney's (2017) observations about silicone as favourable swipe material. The lubricating spray created a liquid film, which reduced adhesion of faeces to the bowl's surface, thus improving the cleanliness of the prototype. This is one effect of water in water-flush toilets. While a thin film requires far less liquid than even low-volume flush toilets, and such an amount would likely be a valuable use of water for the sake of user acceptance, the idea of an entirely dry flush would be lost were the lubricating spray implemented.

All swipe materials had difficulties removing soft-glutinous synthetic faeces, and the tests using synthetic menstrual fluid highlighted a problem removing blood-stains from the bowl. The fact that the families participating in the household tests used water to keep the prototype clean emphasizes that the dry swipe alone does not yet provide satisfactory cleaning performance. Considering that there is a distinction between actual cleanliness and perceived cleanliness, (Orstad *et al.*, 2017; Vos, Galetzka, Mobach, van Hagen, *et al.*, 2018a) a thorough investigation into the stimuli affecting the perception of cleanliness could help focus the development efforts of the mechanical flush. With a combination of design improvements, informed choice of materials, and maintenance protocols, the mechanical flush's cleanliness – and the perception of its cleanliness – could potentially be improved to the level of a porcelain water flush toilet. A customised cleaning utensil for the mechanical flush could facilitate the cleaning process. Fouling in water flush toilets is a common occurrence, both in institutional and household toilets. While the use of toilet brushes is widely accepted in private settings, personal observations would indicate that in public settings, this is not always the case. The authors could not find published studies on the use of toilet brushes, private or institutional. Future user tests of a re-designed prototype could benefit from a parallel investigation of the user habits and cleanliness of institutional water flush toilets.

As an example of the potential for optimisation, the material used for the bowl (polyurethane) was chosen for practical reasons of prototype manufacture and will likely change in the final product, e.g. to reduce the adhesion of faeces. A material or functionalised surface has to be both hydrophobic and oleophobic to fully repel faeces, as they contain both fats and water (Rose *et al.*, 2015). Research on such *omniphobic* surfaces is ongoing (e.g. Wang *et al.*, 2016; Zhu *et al.*, 2017), and could find implementation in the mechanical flush. Such a surface could provide a similar effect as the lubricating spray did, enabling the toilet flush to remain purely mechanical and to not require lubricants.

During household testing, the materials used in the prototype exhibited fatigue, causing failures in moving parts and reduction in swipe efficiency. This is another indicator that further research in material selection is required. The prototype was mainly produced from polyurethane. This is not an unusual choice: portable chemical toilets tend to be made from polyurethane, the UDDT pedestals used in the eThekwini municipality are made from polypropylene (Personal communication with Jacques Rust, Envirosan, Republic of South Africa), and the 'Blue Diversion Toilet' developed by EAWAG (2014; Tobias et al., 2017) is largely made from LLDPE plastic. Given that plastics are cheap, light, durable, and easily available materials, this is unsurprising. Nonetheless, care must be taken to ensure long term durability of all parts in a final product.

The surveys and interviews at UKZN need to be analysed in the knowledge that most users of the prototype, and all interviewees, were members, students, or affiliates of the PRG at UKZN. This means they were well used to working with faecal material and likely perceived sanitation systems differently to the general public. While their opinions are therefore not necessarily generalizable, they likely possessed valuable insights into important aspects of a well-working sanitation technology for use in a water-scarce setting. In addition, these users might be more likely to openly discuss toilet-related matters than the general public. This makes their opinions a useful resource for the next design-iteration of the mechanical toilet flush. Analysing their perception and opinions showed that most users in an institutional setting, who are accustomed to water flush toilets, thought the prototype was easy to use and found odour and cleanliness to be acceptable. However, hygiene, and the process of keeping the toilet bowl clean from both faecal material and menstrual fluid, was a significant concern for these users. The complete lack of water seemed to be problematic to many of them, several of whom suggested installing an automated version of the pump action spray bottle. This highlights the importance of perceived cleanliness (Whitehead, May and Agahi, 2007; Vos, Galetzka, Mobach, van Hagen, *et al.*, 2018b) – it seems that users accustomed to a water flush toilet feel the mechanical flush has a lower level of cleanliness than its aqueous counterpart, even when they are involved in research on dry sanitation technologies. At the same time, the users in households, being accustomed to UDDT-pedestals, perceived the prototype more positively. While flush toilets are still the aspired product for inhabitants of eThekwini municipality (Mkhize *et al.*, 2017), a toilet pedestal designed to look similar to a porcelain toilet and incorporating a waterless mechanical flush seems to be a viable alternative, as long as it is reliably clean and robust.

The swipe tests in the laboratory were a useful simulation of different bodily excreta being flushed, and they confirmed the preliminary findings from the field trials. However, using photography and image analysis to gauge removal rates does not produce perfect results, since the bowl's three-dimensional surface is analysed in a two-dimensional photograph. Photogrammetric methods to develop a three-dimensional image from several two-dimensional photographs of the same object, for example used in medical (Patias, 2002) and forensic research (Urbanová, Hejna and Jurda, 2015), could be used to deliver more accurate results.

Even though the tests with SMF were inconclusive, they produced the valuable information that the mechanical flush is not yet able to clean blood stains from the toilet bowl. It should, however, be noted that the SMF is only an approximation of real menstrual fluid, and a tampon in real use would not always be as fully soaked as in this experiment (nor would it necessarily be flushed down a toilet). As research into menstrual hygiene management progresses, more accurate methods of simulating menstruation may be developed. Considering the taboos around the subject (Hertz, 2018), the effective removal of blood stains is an important requirement for the acceptance of a mechanical flush.

The mentioned lack of a bin in the toilet room at UKZN likely contributed to the decision of those who menstruate to avoid using the prototype during menses. This was clearly an oversight by the installation team, none of whom menstruate. It indicates a need for greater awareness of menstrual hygiene management issues during preparation of field testing.

2.5.1 Design recommendations

The identified issues with the current prototype design and the users' attitudes translate into several design recommendations:

1. An automated lubricant spray, activated upon opening and/or closing the toilets lid, could improve the cleanliness in the bowl by lubricating the bowls surface prior to use and moving toilet paper from the pan into the bowl. Additionally, this could improve the perception of cleanliness for users accustomed to water flush toilets. This would, however, require a small reservoir of lubricant, and the flush would no longer be completely dry.

2. Deepening the toilet pan / bowl would leave more space between the user and the faeces and reduce the risk of physical contact between the user and the bowl.
3. A change in the pan's geometry would eliminate the issue of urine residue in the pan.
4. Increasing the size of the swipe would increase the contact between swipe and the bowl's surface, and thus the swiping activity.
5. The material for the rotating bowl and the swipe should be resistant to fouling, e.g. with an omniphobic surface, and have a high mechanical strength. If the adhesion of faeces and menstrual fluid is sufficiently low, this could replace the need for the automated lubricant spray.
6. User Guidance on cleaning a waterless toilet could help to ensure that no excess water or inappropriate cleaning chemicals are used.

These recommendations are the result of combined field- and laboratory testing, and will serve as basis for the re-design process of the mechanical flush's next iteration. A re-designed prototype pedestal can then be tested to assess whether the performance and user perception have improved.

Considering the number of design-decisions that have yet to be made in refining the current prototype, for example the selection of materials, the design for manufacture at larger scale, and the location of production, a realistic estimate of the cost of the final product cannot be made at this point.

2.6 Conclusions

In field trials and controlled laboratory experiments, the functionality of a mechanical flush prototype was evaluated.

- It was effective in moving most faecal matter out of the toilet bowl and provided an acceptable odour barrier between faecal material underneath and the environment. Fouling in the bowl was still a persistent problem.
- The laboratory tests gave insight into the selection of swipe material, showing that silicone-based swipes performed better than a polyurethane

rubber. They also demonstrated the value of lubricating the bowl before use.

- All swipe materials tested could not sufficiently clean soft-glutinous faeces or blood stains off the bowl's surface, emphasising the difficulty to develop a waterless flush.

Further research should focus on improving the bowl's resistance to fouling as well as the swipe's ability to remove any fouling left in the bowl. Valuable lessons were learned about the potential areas of improvement, and design recommendations were made to inform the next iteration step in developing the mechanical waterless flush. Implemented into other waterless sanitation systems, it could significantly improve their acceptance. Altogether, this study serves as an example of the effective combination of different approaches to increase the insight gained from testing a prototype.

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2.9 Appendix

2.9.1 Appendix A – Survey Questionnaire for User Testing at UKZN

Please answer these questions each time after using the Nano Membrane Toilet:

(simply circle your answer)

A. I identify as: Female Male Other X rather not say

B. I used the toilet this time: Yes No

C. I used the toilet for: 1. Urinating only 2. Defecating

D. How much do you agree with the following statements?

1. The toilet didn't smell bad: ☹ 😐 ☺

2. The toilet was clean: ☹ 😐 ☺

3. Using the toilet was easy: ☹ 😐 ☺

4. I prefer using this toilet to my usual toilet: ☹ 😐 ☺

Figure 2-6: Survey questionnaire for user testing at UKZN

2.9.2 Appendix B – Table of topics for user interviews at UKZN

Table 2-7: Topics covered in the semi-structured interviews with users of the prototype at UKZN.

Likes and dislikes about the toilet
Smell
Cleanliness
Challenges using the toilet
Difficulties Cleaning the toilet
Menstrual hygiene management (MHM; was only discussed with female interviewees)
Comparison to usual toilet
Toilet location
Cultural and religious norms
Overall experience

2.9.3 Appendix C – Procedure for determining fouling removal rate

In *ImageJ* software, the area of the rotating bowl was determined in each picture by tracing its outline, using the *polygon selection tool* and measuring the area within in pixels. Then, with the *Color threshold* tool, the area covered in synthetic faeces was determined, using the following settings:

- *Hue* and *Brightness*: set to full range
- *Saturation*: from 50 to 255.

These settings were found to capture the faeces in the image, but not the white bowl, or shadows therein. Every photograph had to be analysed individually, because the zoom changed slightly between photographs. Figure 2-7 demonstrates the process.

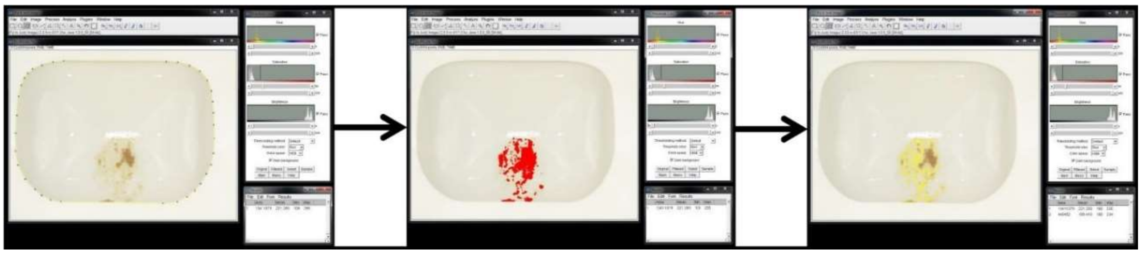

Figure 2-7: Using ImageJ Software to determine covered area in toilet bowl.

The covered areas before and after flushing (measured in pixels) could be compared as ratios to the area of the bowl. The removal rate was calculated from the ratio of these ratios before to after flushing, as seen in Equation (2-1).

2.9.4 Appendix D – Recipe for Synthetic Faeces

To increase adhesion of residue on the toilet bowl's surface, peanut oil was removed from the original recipe and plain white wheat flour was added. In the quantities used for this study (200 g synthetic faeces at a time), it was feasible to simplify the portions of all ingredients by rounding to the closest multiple of 5 g:

Table 2-8: Simplified recipe for 200 g synthetic faeces.

40 g dry brewer's yeast
20 g psyllium husks
5 g plain white wheat flour
15 g Miso paste
15 g Polyethylene glycol (PEG) 4000
15 g $CaPO_3$

10 g cellulose powder
80 g deionised water
First, all dry ingredients are mixed together, then the Miso paste and water are added. Everything is stirred thoroughly.

2.9.5 Appendix E – Bristol Stool Chart

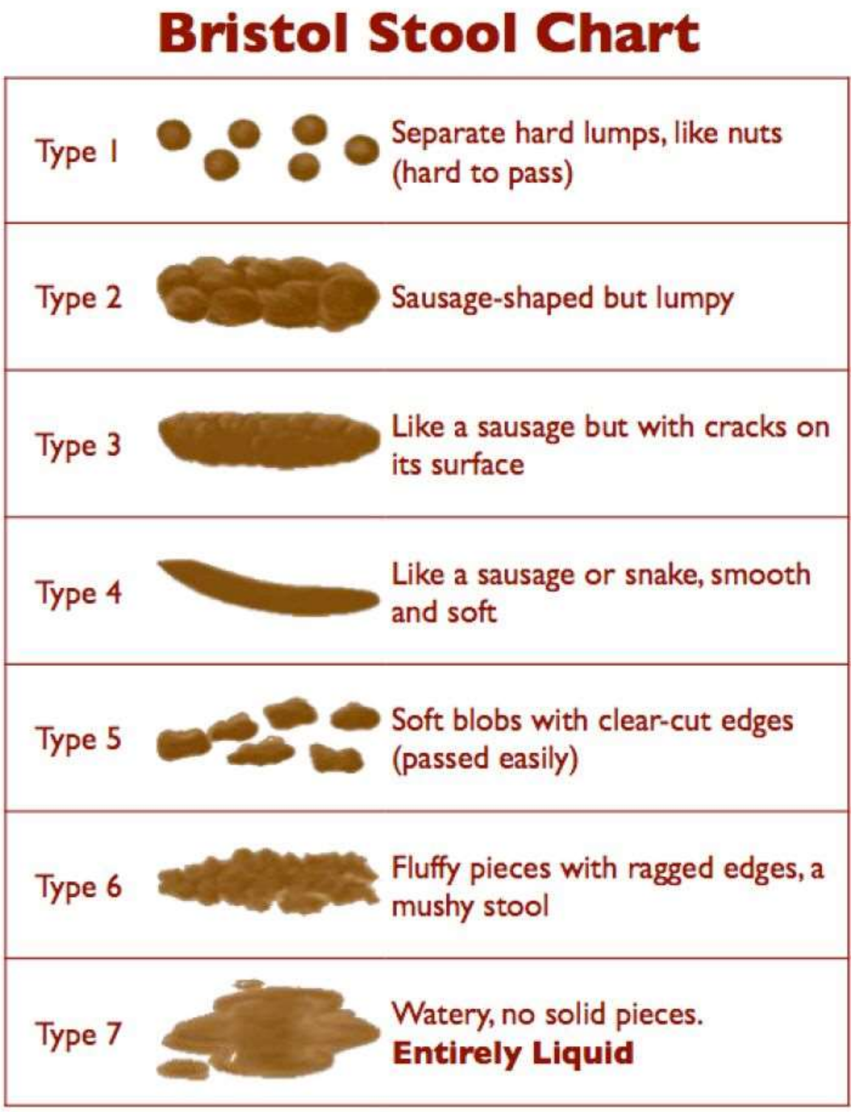

Figure 2-8: Bristol Stool Chart; image created by Kyle Thompson for Michigan Medicine, University of Michigan, under a Creative Commons Attribution-NonCommercial-ShareAlike 3.0 Unported License.

Preface to chapter 3

The prototype tested in the previous chapter (Chapter 2) was called the HUT2 prototype, with HUT being an acronym for Human User Testing. It was developed and built to demonstrate the design of the NMT's front end and the functionality of the mechanical flush. It was designed for field tests, i.e. to be installed into existing sanitation infrastructure and used as toilet. Chapter 2 describes these field tests, as well as later laboratory tests with this prototype.

These tests were planned and conducted by a testing team, rather than the design team which built the prototypes. The prototype was developed before the testing team started planning the tests. Thus, the testing team could not communicate their needs to the design team, and their requirements for the prototype tests were not considered in the design of the prototype. Therefore, the tests had to be designed around the existing design, limiting the possibilities of investigation. It seems plausible to assume that the tests could have yielded results of higher quantity, quality, or both, had the tests been planned before, or during, the development of the prototype, and had the testing and design teams cooperated more closely.

The lessons learnt from the tests described in Chapter 2 informed a new design iteration of the NMT front end, the *HUT3* – prototype. Furthermore, they informed the design of improved tests to be conducted in field trials of this prototype. However, the attempts to improve the prototype's functionality based on the design recommendations did not lead to a second round of testing. Instead, preliminary laboratory tests of the prototype showed that it could not be used for the planned field trials in its current form. Some design recommendations listed in Chapter 2 were implemented successfully. For example, the toilet pan was deepened, and its geometry altered slightly to avoid the retention of urine at the edge to the rotating bowl. Also, a semi-automatic spray device was included following the HUT2 test findings regarding the efficiency of pre-spray. However, other improvements were unsuccessful so far. For example, an attempt to improve the rotating mechanism's robustness resulted in the swipe not clearing the entire surface of the rotating bowl in preliminary tests. Furthermore, the collection tank underneath the bowl was not sufficiently waterproof in the HUT3 prototype. At least partially, these problems can likely be attributed to insufficient communication between design and testing teams.

The following chapter (Chapter 3) will theorise that a holistic understanding of a prototype testing strategy could aid in planning and communicating prototype tests according to the needs of the entire Product Development (PD) process and propose a visual tool to convey this holistic understanding. It is my contention that such a tool could have been used by the testing and design teams respectively to better coordinate the design of the prototypes and plan their tests.

3 Planning and communicating prototype tests for the Nano Membrane Toilet: A critical review and proposed visual tool

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Declarations of interest: none

3.1 Abstract

Urban sanitation in growing cities of the Global South presents particular challenges, like the speed of their growth, the high population density, and, often, the lack of existing wastewater infrastructure. This led to the Bill & Melinda Gates Foundation's Reinvent The Toilet Challenge, a call to develop novel, non-sewered sanitation technologies, which sparked the development of various inventions, like the Nano Membrane Toilet. Complex technologies like this entail an extensive product development process, including various iterations of prototype tests. While there is an abundance of literature discussing how to build prototypes, and the optimal number of tests, there has been little focus on how to plan, communicate, and conduct tests, especially in a product development endeavour of this complexity. Multiple aspects of testing prototypes are reviewed. A visual test planning tool is proposed that encompasses the entire product development process and can be used to plan and communicate prototype tests for the Nano Membrane Toilet to ultimately achieve compliance with international standards.

Abbreviations

ALT – Accelerated Life Testing; BMGF – Bill and Melinda Gates Foundation; DOE – Design Of Experiments; HALT – Highly Accelerated Life Testing; ISO –

International Organization for Standardization; NMT – Nano Membrane Toilet; PD - Product Development; RTTC – Reinvent The Toilet Challenge; UCD - User Centred Design; UDDT – Urine Diversion Dry Toilet

3.2 Introduction

To develop novel complex products, e.g. non-sewered sanitation technologies like Cranfield University's Nano Membrane Toilet (NMT), fundamental research and creative design techniques have to be performed in combination, and building and testing physical prototypes is a crucial part of this process (Tahera, Eckert and Earl, 2015). Larsen *et al.* (2016) acknowledge that, for technologies addressing urban water challenges, testing of technologies has to occur with a variety of methods to ensure robust, affordable, accepted and applicable solutions. Camburn *et al.*, (2017) point out that prototyping is most well-known for design refinement.

What constitutes a complex product can vary depending on the research question. A common definition is that a complex product "consists of a set of sub-products", where "a sub-product may represent a specific piece of equipment, a business service, or a software-based service […]. Sub-products can also be composite, in the sense that they may consist of other sub-products" (Afsarmanesh and Shafahi, 2013). According to Luo *et al.* (2016), developing complex products often has a multidisciplinary character, and research and development is complicated. Hobday (1998) emphasizes the numerous dimensions of complexity a product can have: "The term 'complex' is used to reflect the number of customised components, the breadth of knowledge and skills required and the degree of new knowledge involved in production, as well as other critical product dimensions.", and, building on this, Ljunggren Söderman and André (2019) add a "product chain dimension" and a "temporal dimension" to describe product complexity. For the purpose of this paper, a complex product is *a product that comprises multiple sub-products and technologies, thus requiring a greater development effort than simple, mass-produced products.* An example of such greater development efforts can be the use of a large number of physical prototypes.

Ulrich and Eppinger (2016) define a prototype very broadly as “an approximation of the product along one or more dimensions”. They furthermore identify four purposes of prototypes: learning, communication, integration, and milestones. Prototypes can also be categorised by how closely they resemble the final product, i.e. their fidelity (Mccurdy *et al.*, 2006). Another important distinction of different categories of prototypes is between virtual and physical prototypes, and the use of virtual prototypes, or simulations, has increasingly gained importance in the past decades (Tahera, Earl and Eckert, 2014). However, as the complicated interactions between the sub-products of a complex product will often be too difficult to simulate, this paper is focused on the testing of physical prototypes, as opposed to “the solution of analytical models and numerical approximations” (Boës *et al.*, 2017).

In the context of prototype testing, the main purpose of a prototype is learning. Tronvoll *et al.* (2017) write about the use of prototypes: “A prototype experiment often targets generating knowledge about different attributes of a proposed design which is not identified by simple reflection.” Similarly, the IEEE (1990) gives a definition of testing, shared by (Tahera *et al.*, 2019), as “an activity in which a system or component is executed under specific conditions, the results are observed or recorded, and an evaluation is made of some aspect of the system or component.” In combination, we define prototype testing as *knowledge-generating activity in which a prototype is executed under defined conditions, the results are observed or recorded, and an evaluation is made of some attributes of the prototype.* Prototype tests, like most activities in Product Development (PD) processes, can be seen as risk-reduction tasks (Keizer and Halman, 2009; Unger and Eppinger, 2011).

There is ample literature advising on how to design and build prototypes according to testing needs (e.g. Camburn *et al.*, 2015; Menold, Jablokow and Simpson, 2017), and on testing strategies that aim to optimise the time and number of prototype tests (e.g. Thomke and Bell, 2001; Al Kindi and Abbas, 2010; Qian *et al.*, 2010). Camburn *et al.* (2017) thoroughly review the literature regarding strategies, techniques, and guidelines of prototyping. However, the question of *how* to test prototypes is seldom answered (Tahera, Eckert and Earl, 2015), especially not with consideration of the entire PD process. Batliner *et al.* (2018), for instance, complain about the under-representation of general testing methodology in engineering literature impeding its integration into an engineering design curriculum. The planning of prototype testing, and communicating these plans, can therefore be difficult in the multi-disciplinary groups working on a PD project like for the NMT, and a tool to aid in these activities could be of great use. While different aspects of testing like iteration (Wynn and Eckert, 2017), usability testing (Unger Unruh and Canciglieri Junior, 2018), design of experiments (DOE) (Ilzarbe *et al.*, 2008), Reliability Testing (Bhamare, Prakash and Ajay, 2007; Zhang *et al.*, 2014) and international standard compliance (Tyas, 2009; Shin, Kim and Hwang, 2015) are well understood in their respective fields, a synthesis of these aspects could be used to develop a holistic test-planning tool for products like the NMT. Keller *et al.* (2006) discuss the difficulties faced by people developing large and complex products keeping an overview over the entire project and communicating their work to colleagues. They propose an improved way to visualise design processes to overcome this problem. Similarly, a visual tool that achieves synergy of different aspects of testing prototypes could be useful in planning and communicating testing efforts for the development of a complex technology like the NMT. The result could be more effective tests yielding more valid and useful data, as well as an increase in efficiency throughout the PD process. Future studies could use this tool developed from existing literature as basis to further develop it towards general applicability for prototype testing in PD by drawing from unreported expert knowledge of testing and engineering design.

This paper aims to review various aspects of testing prototypes to then propose a visual test planning tool to facilitate planning and communication of prototype testing for the development of the NMT.

3.3 Methods

3.3.1 Case Study: The NMT, a complex product

Sanitation, the containment, transport, and treatment of human excrements, is a topic of high significance for human development (Jahan, 2016): UNICEF (2017) stress the importance of safe sanitation for children's health and that improving (access to) sanitation could reduce child mortality. Lack of sanitation has been linked to reduced cognitive development in children (Sclar *et al.*, 2017) as well as stunting, caused by environmental enteric dysfunction (Budge *et al.*, 2019), and to a risk of assault, particularly for women and girls practicing open defecation (Jadhav, Weitzman and Smith-Greenaway, 2016; Miiro *et al.*, 2018).

Urban sanitation poses particular difficulties, due to the lack of piped water and prohibitively high cost of sewer systems (Parnell, Simon and Vogel, 2007; Cobbinah and Poku-Boansi, 2018). The most commonly promoted sanitation systems in cities of the Global South involve toilets that use little to no water, i.e. dry toilets, and store the faecal material onsite. Examples of this are pit latrines, pour-flush toilets, urine-diversion dry toilets (UDDT), and septic tanks (Semiyaga *et al.*, 2015). When full, these toilets are emptied, and the faecal sludge is transported and either treated and reclaimed or discharged, or discharged without treatment. However, there are problems with these sewer-less sanitation services, such as high fees for emptying services, collection and transport trucks not being able to access the houses, high transport costs to treatment facilities or the altogether lack of such facilities (Strande, 2014). Another obstacle for the success of these technologies is public acceptance: Users can consider the pedestals of dry toilets uncomfortable, dirty, or malodorous, and they may worry their children could fall into the pit (Roma *et al.*, 2013; Mkhize *et al.*, 2017).

To find a solution to these problems, the Bill & Melinda Gates Foundation (BMGF) initiated the *Reinvent The Toilet Challenge* (RTTC) to "create a toilet that:

- Removes germs from human waste and recovers valuable resources such as energy, clean water, and nutrients,

- Operates “off the grid” without connections to water, sewer, or electrical lines,
- Costs less than US$0.05 per user per day,
- Promotes sustainable and financially profitable sanitation services and businesses that operate in poor, urban settings, [and]
- Is a truly aspirational next-generation product that everyone will want to use – in developed as well as developing nations.” (BMGF, 2013)

As result, research institutions and companies worldwide are now developing waterless, non-sewered sanitation technologies (BMGF, 2013). The reinvention of the toilet requires unconventional thinking. Niemeier *et al.* (2014) discuss the challenges of building technologies for the development context: “If we are to resolve global inequities in access to innovations that improve health, we must adopt new approaches to engineering design that reflect the unique needs and constraints of low-resource settings”. They further mention how “efforts like the [RTTC] reflect the kind of integrative thinking that must occur at the beginning of a design initiative […]”. One example of a reinvented toilet is the NMT, conceived by researchers at Cranfield University (Parker, 2014). The NMT is a household-level, onsite sanitation system that looks similar to a porcelain water flush toilet (Figure 3-1 and Figure 3-2). It uses combustion and membrane processes to treat the mechanically separated solid and liquid waste streams. With all its components, the NMT would not just replace the currently existing dry toilet technologies, but also the associated faecal sludge management services, thus offering a form of safely managed sanitation (WHO and UNICEF, 2017). It is not simply a human waste receptor, but rather a miniature faecal sludge treatment facility.

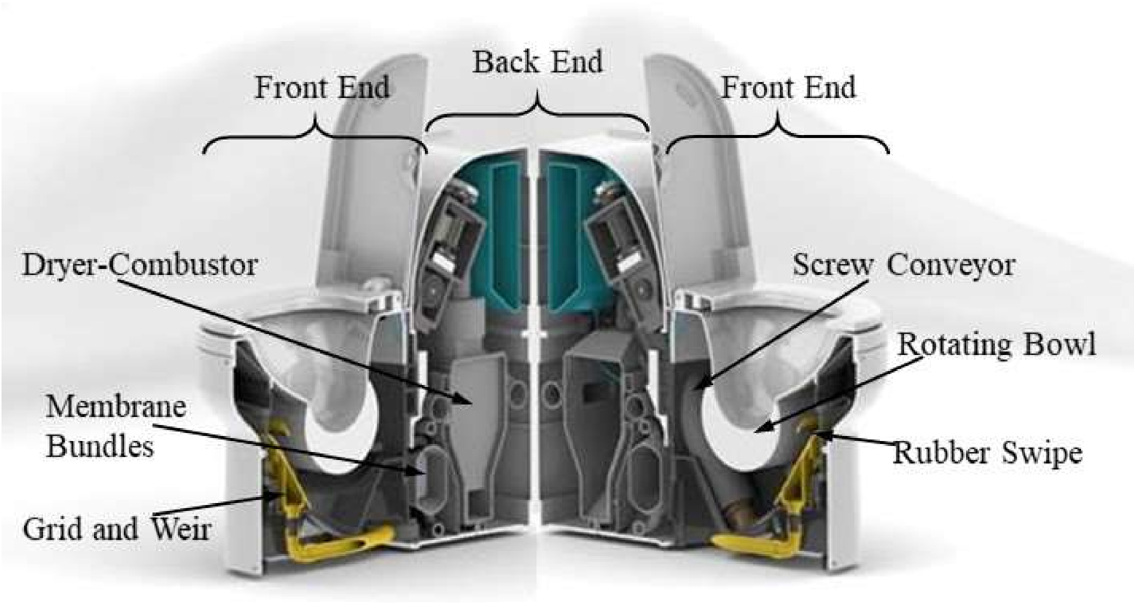

Figure 3-1: Conceptual schematic of the NMT and its components. The front end comprises the mechanical flush with its rotating bowl and rubber swipe, the collection tank with the grid and weir and the screw conveyor. The back end consists of the dryer, the combustor, and the membrane bundles.

Figure 3-2: Figure 2. Nano Membrane Toilet front-end prototype.

Naturally, there are numerous considerations to be made during the development of such a technology. The NMT combines entirely novel technologies with already existing ones. However, even for the well-established technologies, their application for this specific purpose is novel, and requires further research in order to miniaturise, integrate and optimise for off-grid functionality. At the same time, from a user's perspective, not much should change when transitioning from using another dry toilet or a porcelain flush toilet to the NMT. To fulfil the RTTC's demand for an aspirational design (Bill & Melinda Gates Foundation, 2018), it should be comfortable, appealing, and simple to use. It should take into account the preferences and customs of users from a diverse range of cultural backgrounds. Fejerskov (2017) emphasizes the importance of considering the users of a newly developed technology: "[…] a technology developed in isolation from those who are supposed to benefit from it cannot be expected to wield predictable outcomes." There is research on the preferences of toilet users in various contexts, from industrial nations like the Republic of Korea (Lee, 2019) and Canada (Morales *et al.*, 2017), to a focus on elderly users (Dekker, Buzink and Molenbroek, 2011) to low- and middle income countries (Nelson *et al.*, 2014; Austin-Breneman and Yang, 2017). Hence, developing the NMT entails developing a user-friendly user interface—in software development projects this would be called "front end" (Reza and Grant, 2007)—and a "back end" comprising several sub-technologies, and integrating them into the overall system.

The RTTC has thus led to an unusual case of PD at this scale: It asks for a product that connects existing notions of a toilet's function and design with never-before-seen technologies. A viable solution to the problems associated with dry sanitation must simultaneously satisfy users' ideas of aesthetics and comfort, and adhere to high standards of safety and reliability.

The NMT is a complex product, which is, in fact, a combination of sub-products that have to be developed individually and then integrated into the overall system. The original design brief for the NMT was the RTTC, which included important user-centred objectives of aspirational design and affordability, as well as objectives aiming at sustainability and at solving the problems of urban non-sewered sanitation (Bill & Melinda Gates Foundation, 2013). From this, initial design ideas were conceived involving membrane treatment of liquids and water recovery through condensing beads, as well as the drying and coating of solids (Parker, 2014). Later design stages discarded the condensing beads and a combustion process was devised to replace the coating of solids. Considering that the user of the toilet would usually not interact directly with the treatment processes, these were not subjected to user testing yet. The pedestal, the part of the toilet with which the user interacts, mainly differs from a porcelain water flush toilet in its mechanical flush. It was developed as the result of studies among potential users in Ghana and subsequent agile innovation processes (Tierney, 2017). Several iterations of prototypes were produced to develop a mechanical flush, until it could be tested in real-use scenarios.

This mechanical flush – a rotating bowl and rubber swipe activated by moving the toilet lid – separates the user from a tank underneath the toilet pan (Tierney, 2014, 2017). Solids are separated through settling and displacement, transported by an screw conveyor (E. Mercer *et al.*, 2016) and subsequently dried and combusted (Onabanjo, Kolios, *et al.*, 2016; Fidalgo *et al.*, 2019), while the liquid fraction is extracted through a weir and purified through membrane processes (Wang *et al.*, 2017; Kamranvand *et al.*, 2018), driven by the heat of the combustion, which is transferred via a heat exchanger (Hanak *et al.*, 2016). The toilet pedestal, including the mechanical flush, the screw conveyor, and the liquid weir are considered the NMT's front end. The dryer, combustor, and membrane components are considered its back end. The NMT is envisioned to be independent of water- or sewer connections and energy neutral, or even have a positive net power output (Kolios *et al.*, 2018). However, the back end components have not yet been integrated and combined with the front end to produce a fully functioning prototype of the NMT. Such tasks are envisioned to be conducted in the near future.

At the moment, all sub-products which the NMT comprises are in an iterative phase of building and testing prototypes. The front end has been re-designed as result of field tests involving target users of the NMT (Hennigs, Ravndal, *et al.*, 2019). Prototypes of the dryer and combustor (Jurado *et al.*, 2018) have been tested in the lab in several iterations. In addition, the recovery of electrical energy by reverse electro-dialysis is under investigation (Hulme *et al.*, in preparation).

This means that the individual components and sub-products of the NMT are developed enough to plan for integration of all sub-products into a complete prototype. Such a prototype would then be tested in laboratory tests, and once its safe operation was sufficiently proven, it could be deployed for user-centred field tests. The aim of such tests, and concurrent further sub-product improvements, would be to optimise the operational settings of the entire system. The recently published ISO 30500 standard (ISO, 2018) could provide the benchmark performance values the prototype has to achieve. Once the prototype meets these values, its design can be polished for usability and manufacture. Final reliability and user tests of this polished design would ensure the NMT's usability and reliable functionality throughout its lifetime, and when passed, allow this design to confidently be tested for ISO 30500 standard-compliance, making it a market-ready product.

Consequently, there are still numerous prototype tests which need to be planned and conducted. The development and testing of prototypes of the NMT's various sub-products to date have not been guided by a visual test planning tool. Instead, prototypes of components were usually developed and tested by the teams working on these components. In the case of the front end, however, a prototype was developed by one team, the design team, and then tested by another, the testing team (Hennigs, Ravndal, *et al.*, 2019). Because the two teams did not communicate extensively with each other when developing the prototype and testing procedures respectively, a prototype that was not developed for specific testing purposes was built first, and tests then had to be developed for that prototype. Therefore, the testing procedures were limited by its capabilities. This led to an expensive set of field tests yielding results that could conceivably have been achieved cheaper by testing prototypes of individual components specifically developed for the testing purposes. It could therefore be possible that the prototype tests to date could have been conducted more effectively had they been planned in a more coordinated manner. Similarly, the communication within and between the various teams working on the NMT could benefit from a more consolidated terminology and shared understanding of the development process and the associated testing activities. A visual test planning tool could thus facilitate and improve the planning and communication of testing activities in the future.

3.3.2 Literature Review

Using our own publications and those of our colleagues on the project, the development history of the NMT was established as that of a complex product and outlined in the section above. Subsequently, the Scopus and Google Scholar databases were used for an exploratory search of peer reviewed literature, with a focus on literature reviews covering a range of publications, to advance the understanding of the broad field of prototype testing in PD. Search terms included *review, prototyping, prototype testing, product development, technology development, testing,* and others. Using these terms in various combinations, promising publications were identified and studied individually. In the search, several repeatedly occurring aspects of testing prototypes were identified and then further investigated in a more targeted search on the same databases. The aspects were *types of prototype tests, phases of the PD process, iteration, usability testing and user centred design, reliability testing, testing for standard compliance, design of experiments, back end and front end testing, and visualisations of PD processes*. They were chosen for further investigation because of their repeated occurrence in the literature and their apparent applicability for the context of this paper. Again, the focus of the resulting search was on reviews of the existing literature rather than original work, as the aim was to obtain a wide understanding of multiple fields of study, rather than an in-depth analysis of a single one. Similar search terms were used, with the addition of the identified testing aspects. The identified literature was then analysed to extract the information relevant to prototype testing activities, particularly for the development of complex technologies. This analysis yielded the section ‘relevant aspects of prototype testing’.

3.3.3 Creating a visual test planning tool

A visualisation of the prototype testing processes for the PD of the NMT was then conceived, with the aim to consolidate the collected information. A simple linear PD process model was chosen, divided into three phases, with parallel strands of testing for the front end and back end, considering different types of testing, DOE, usability testing, reliability/durability testing, and international standards at different stages of the process, and possible iteration loops throughout the process.

3.4 Relevant aspects of prototype testing

While the route to technological maturity of a product may seem straight-forward, each step can involve extensive preparations and cooperation among multiple teams. It is sensible to separate the PD process into distinct phases, which involve distinct activities (Rubin and Chisnell, 2008). To maintain an overview of the progress, a visualisation of the entire PD process can be valuable (Keller *et al.*, 2006). “Iteration is a fact of life in any [PD] project”, particularly for complex products (Wynn and Eckert, 2017). It should thus be considered when planning testing activities, as well as the fact that these tests can be of different types, in different settings, with different aims and methodologies (Boës *et al.,* 2017). In the example of the NMT, prototype integration not only requires a sufficient level of maturity of all sub-products, but also operational process control to connect all sub-products with each other considering their complex interactions. This requires extensive knowledge of all sub-products’ operational conditions, which may be acquired in tests that Boës *et al.* (2017) would classify as experiment tests, using statistical DOE (Ilzarbe *et al.*, 2008). Reliability and durability estimation methods are needed to ensure the system’s reliability and durability throughout its lifecycle (Bhamare, Prakash and Ajay, 2007), and often national or international standards exist to ensure the technology is safe to use (Feo-Arenis *et al.*, 2016). Additionally, as mentioned in the introduction, prototype and system tests need to be centred on the target users of the technology. If they do not want to use a novel toilet, it will fail to have a positive impact on the sanitation crisis. Methods of UCD, e.g. usability testing, can be used to avoid such failures (Unger

Unruh and Canciglieri Junior, 2018). In complex products, it is likely that the users will only interact with parts of the product, the user interface. It can therefore be sensible to consider testing efforts separately, as is common in software development, where front end and back end are tested separately (Bertolino, 2007).

In the following subsections, the principles of these aspects of testing prototypes are presented.

3.4.1 Types of prototype tests

Boës *et al.* (2017) define testing in the context of PD as "exposing a physical system to a condition or situation in order to observe the system's response." They then clarify the physical system as a representation of the product or one of its components, the condition or situation as a "use case as a whole or its effect on a subsystem", and the system's response as "the performance of a desired function [or] an undesired failure mode." Using this definition, they propose four categories of testing activities according to the type of knowledge that is generated. First, trial and error tests can be used to gain a basic understanding of the development project and to explore the design space. Secondly, experiment tests resemble experimental work in fundamental scientific research in their structured approach in order to identify influencing factors and develop "necessary system knowledge". Thirdly, verification tests are usually pass/fail tests to determine if the system- or component prototype fulfils the requirements set at the beginning of the PD process. Lastly, validation tests determine whether the product addresses the underlying user needs, rather than the requirements set by the product developer. They are commonly conducted with a fully functional prototype.

Camburn *et al.*, (2017) comprehensively review the state of the art in prototyping techniques, strategies, and guidelines, and devise a visual framework to connect prototyping objectives to techniques. They clearly distinguish prototypes from design concepts by stating that prototypes are always tied to tests. They discuss literature on preparing for prototyping, enhancing prototype performance, reducing cost and time, and fabricating prototypes, before reflecting on prototyping science. While they don't specifically identify types of prototype tests, they do list frequently cited prototyping objectives, namely active learning, exploration, communication, and refinement. They further develop scales of prototype distinction, i.e. "*system (isolated or integrated); media (virtual or physical); requirements (relaxed or final); and scale (reduced or final)*". They also discuss iterative prototyping, parallel prototyping, requirement relaxation, subsystem isolation, scaled prototyping, and virtual prototyping as individual prototyping techniques.

There seems to be the implication that there are different types of tests being conducted throughout the PD process that differ in their level of formality, in their approach, and in the knowledge they are designed to produce. A similar observation can be made about the prototyping tests for the NMT. We have identified three distinct types of prototype tests conducted so far, namely user tests, laboratory tests, and field tests. These types of tests can coincide and overlap: just for one generation of a front-end prototype, Hennigs *et al.* (2019) conducted user surveys and interviews (user tests), photography and image analysis (laboratory tests), and field tests on the material choice of a rubber swipe and the long-term robustness of the prototype (field tests). A fourth type of tests are international standard tests. In the case of the NMT, these would be described in the standard *ISO 30500:2018 Non-sewered sanitation systems* (ISO, 2018).

3.4.2 Phases of the product development process

In the case of usability testing, Rubin and Chisnell (2008) distinguish three phases of testing: First, exploratory tests are conducted in the early stages of PD, to test its basic design, i.e. whether users find it intuitively appealing. Then, assessment tests, conducted about halfway through the development process, expand the knowledge on the product's usability, i.e. whether users can perform the intended tasks on the product. Lastly, the validation/verification tests at the end of the cycle tend not to inform further iteration, but rather confirm that all previously identified problems have been resolved, and that the entire product can be used as intended. In these phases, the basic design, early to well-developed prototypes and the final product are tested on potential users to identify their likes and problems.

In his Stage-Gate model, Cooper (1990) considers five stages between a product idea and a "post implementation review", namely *1. Preliminary assessment; 2. Detailed investigation (business case) preparation; 3. Development; 4. Testing and Validation; and 5. Full production and market launch*. Royce's (1970) Waterfall model comprises seven steps to develop a large computer program: *1. System requirements; 2. Software requirements; 3. Analysis; 4. Program design; 5. Coding; 6. Testing; and 7. Operations.* Similarly, other models of PD processes are also sorted into phases or steps (Boehm, 1988; Forsberg, Mooz and Cotterman, 2005). While testing is a single distinct step in most of such models, the various types of prototyping activities and prototype tests throughout the PD process could also be imagined to be separated into phases as the product's maturity increases. Rubin and Chisnell's (2008) three phases (exploration, assessment, validation/verification) provide a sufficient level of distinction for the present work on the NMT.

For this purpose, the objective of the exploration phase is to explore potential solutions to the design brief, to discard unviable ones, and to gather an understanding of the required development process, i.e. to develop the questions that need to be answered in the assessment phase.

The objective of the assessment phase is to expand the knowledge about the potential product solutions, to answer the questions developed in the exploration phase. The outcome of this phase should be one single, functional prototype.

The objective of the verification and validation phase is to ensure that all questions have been answered, that the product functions as expected and is, in fact, a solution to the design brief.

3.4.3 Iteration

Iteration occurs throughout the PD process and can have different causes and outcomes (Wynn and Eckert, 2017). With its earliest forms dating back to the 1930s (Larman and Basili, 2003), the *sequential testing and refinement of a* *prototype* (Christie *et al.*, 2012) can be welcomed as a driver of positive design change, or seen as a wasteful, costly delay in a PD project (Ballard, 2000; Le, Wynn and Clarkson, 2010; Wynn and Eckert, 2017), but it is undeniable that iteration occurs in nearly every PD process, particularly for complex products (Wynn and Eckert, 2017).

It is common to develop software user interfaces iteratively (Nielsen, 1993). For complex physical products, every iteration-step of building and testing a prototype can be associated with high costs (Tahera *et al.*, 2019). It is therefore important to consider when and how many iteration-steps should be undertaken. Camburn *et al.* (2017) emphasize that iteration should occur often and early in the PD process, and should be encouraged the higher the potential for performance increase and the lower the cost per iteration. The higher the product's maturity, the higher the cost of iteration will likely be. There is a multitude of publications discussing the complex nuances of iteration in PD, and Wynn and Eckert (2017) offer a comprehensive overview and terminology of this field of research: They differentiate between *micro-level* and *macro-level* iterations, as well as between three iterative functions of *progress* toward completion, *correction* of errors, and *coordination* of actors, decisions, or workflows. They assign multiple *iterative stereotypes* to each function: Progressive iteration comprises the stereotypes *exploration, concretisation, convergence, refinement, and incremental completion.* Corrective iteration covers *new work, rework,* and *churn.* Lastly, coordinative iteration encompasses the stereotypes *governance, negotiation, parallelisation, comparison,* and *concentration* (Wynn and Eckert, 2017). This illustrates the complex role that iteration plays in PD.

For the development of an NMT testing tool it is mainly important to know that, while iterative loops can occur throughout the PD process, the value for cost reduces as product maturity increases (Wynn and Eckert, 2017), and to consider which test results should trigger or prevent an iterative loop. With the main goal of the PD process being a marketable product, any proof that a prototype does not represent such a marketable product should be a trigger of iteration. Failed tests, like the shortfall against benchmark values, can be seen as such a proof.

International or internal standards can provide such benchmark values. Cost is a deciding factor and will have to be considered by a project manager when deciding whether to iterate further or not. However, the complex calculations weighing iteration-cost against the cost of having a less well-tested product would go beyond the scope of the present work.

3.4.4 Design of Experiments

Laboratory-based tests commonly involve the observation of a (sub-) product's condition and/or outputs in relation to its inputs. As mentioned above, a comprehensive understanding of the systems' outputs respective to their inputs and process variables is required. Often, there are several inputs and/or outputs for one component, and inputs can interact with each other to create second- or higher-order effects on the outputs (Montgomery, 2009). For example, potential factors that can affect the processes in a combustion chamber are the amount of fuel, its flux, its moisture content and calorific value, the process temperature as well as the flux, pressure, temperature, humidity, and oxygen content of the inflowing air (Jurado *et al.*, 2018).

To test all inputs and their interactions, across their entire range, is either very difficult or impossible. It would take hundreds of tests to assess every factor's influence on the combustion process. Some factors cannot be controlled; some cannot be changed without affecting another.

Based on the work of statistician R.A. Fisher (Yates, 1964; Fisher Box, 1980), DOE uses statistical approaches to address such problems, to minimise the time and effort required for a set of experiments while maximising the validity, reliability, and replicability of information gathered from them. The basic principles of DOE, initially developed for agricultural research, are (Fisher, 1935; Cortes, Simpson and Parker, 2018):

- **Factorisation:** the variation of several experimental factors at once in order to reduce the number of experiments to run.

- **Replication:** the repetition of an experiment with the same settings for experimental factors (treatments) in order to estimate the experimental error.
- **Randomisation:** the random application of treatments and order in which experiments are run, to validate the assumption that the observations and errors are independently distributed variables.
- **Local control of error, or blocking:** the subdivision of experimental runs into homogenous blocks in the attempt to lessen the impact of errors introduced by controllable nuisance factors, e.g. male and female patients in medical drug trials.

It may occur that these principles have to be compromised to some extent for practical reasons, or that complex processes are to be investigated. Within the DOE-toolbox are methods such as split-plot design (Lee Ho, Vivacqua and Santos De Pinho, 2016; Kulahci and Tyssedal, 2017), fractional factorial design, response surface methodology, and random effects models (Montgomery, 2009) for such cases. It is thusly possible to achieve a high level of understanding from comparably few experimental runs. For example, Ilzarbe *et al.* (2008) found in their bibliographical review of 77 DOE applications in the field of engineering, that with an average of 5.06 factors to be investigated, 77% of the studies achieved this goal with 30 or fewer experiments, and 50% with 20 or fewer.

DOE finds application in PD efforts of various kinds: Pineau *et al.* (2019) used a fractional factorial design to assess which design factors of coffee vending machines impacted the sensory experience of the product the most. Gumma and Durgam (2019) improved the structural performance of a car's body using a multi-model DOE sensitivity study, including simulations and experimental model testing. Sano *et al.* (2019) studied Bayesian optimisation techniques to reduce the number of experiments necessary to obtain the information with which they could improve production parameters for orally disintegrating tablets.

Thus, DOE encompasses a wide range of statistical tools for planning how to conduct tests, and how to analyse the results later on, to maximise the statistical validity of the lessons learnt. It does, however, not give any advice on what to test, or why. Other problems with DOE can be that statistical models developed through its use do not accurately reflect the observed processes (Deaconu and Coleman, 2002), or that it gives false credibility to results that stem from badly conducted experiments or the incorrect application of DOE principles. For example, modern technical processes and systems can and must be tested differently to fields of crops (Collins, Hurst and Ard, 2011).

3.4.5 Reliability and Durability Testing

Reliability estimation, a part of reliability engineering, comprises reliability tests and the analysis of the data gathered in those tests. Kapur and Pecht (2014) define reliability as "the ability of a product to function properly within specified performance limits for a specified period of time, under the life-cycle application conditions", i.e., how long a product functions without needing repair. This means that reliability tests are carried out to assess the likelihood of the product—or its components—failing over time. They are usually conducted on prototypes of high maturity, on randomly selected products fresh off the assembly line, or even products that have been in use for a certain time. Similar to DOE, statistical approaches are used to calculate a level of confidence with which a failure will occur in a given time (Kapur and Pecht, 2014).

Durability is a measure of a product's lifetime, i.e. the how long the product can be used until repairs become more expensive than replacing it (Garvin, 1996). In other words, "durability is a particular aspect of reliability" (Tahera *et al.*, 2019). This implies that, while the calculation of durability will involve repair costs and other economic factors, the durability tests to assess likelihood of failure will often be similar or identical to reliability tests. This similarity is reflected in existing literature, where both terms are often used in conjunction (Lee *et al.*, 2015; Munson, Yenal and Lavelle, 2018), and sometimes seemingly synonymously (Bluvband, 2012; Jimenez, 2017).

For both, the challenges lie in accelerating the product's lifetime: It is not feasible to test a statistically significant number of product units over a number of years in order to assess their reliability and durability for this timespan. Therefore, a reliability/durability engineer attempts the realistic emulation of real use scenarios and environmental conditions in a shortened period of time by applying potential stresses, like shock, vibration, or climatic conditions in rapid succession, periodically, or simultaneously (Donovan and Murphy, 2005; Zanoff and Ekwaro-Osire, 2010; Cheon *et al.*, 2015). For this aim, accelerated life testing (ALT) is used to determine a product's time until failure by compressing its lifetime in a short period, usually weeks or months. Highly Accelerated Life Testing (HALT), in contrast, is a technique to determine the most likely failure points of a product but compressing its lifetime into a very short period, usually hours or days (Silverman, 2006).

Difficulties with these approaches lie in the complexity of combined stresses and failure modes, particularly on complex physical products. It is difficult or impossible to "model multiple (or competing) failure mechanism[s] to support reliability testing methods" (Bhamare, Prakash and Ajay, 2007). Furthermore, reliability / durability engineering does not consider the user's experience, but rather focuses solely on the product's reliable functionality. Thus, reliability / durability tests may miss important inputs, as (mis-)use is an important factor in the lifetime of a product, and important outputs, as the user experience may be a more important factor in design changes than increased reliability and durability. For example, a sturdier handheld device may be more reliable and durable, but too heavy or impractical to use.

3.4.6 Testing for technical standard compliance

International "technical standards are established norms or requirements applied to technical systems. They are a crucial aspect of almost all industries […]" (Shin, Kim and Hwang, 2015). They play an important role in technology development (Østebø *et al.*, 2018), by providing "a benchmark for quality and acceptability in the market place" and guidance on the "safety, reliability, efficiency and interchangeability" of products (Tyas, 2009). The testing procedures and performance requirements outlined in technology standards form the basis for the process of ensuring a product is compliant with the standard before being released to market. This does, however, not mean that the first time the standard should be consulted is at the end of the PD process. Instead, the performance, safety and other requirements provide the benchmark to which even early prototypes can be compared, and the testing procedures and-protocols can be adapted or used directly to test prototypes of sufficient technological maturity.

Examples of standards being used as benchmarks during product testing are for a wireless fire alarm (Feo-Arenis *et al.*, 2016), packaging of products (Nolan, 2004), or sensor interface circuits for the automotive industry (Ohletz and Schulze, 2009). Another example is the ‘syngina test’, the standardised test for tampon absorbency. The standard was developed by the American Society for Testing and Materials, when a link between tampon size and toxic shock syndrome was discovered, but customers could not reliably buy tampons of similar absorbency from different brands (Vostral, 2017).

While international standards provide this much-needed guidance, it is important to remember that they are not infallible and may overlook important aspects especially of innovative technologies. For example, Mjör (2002) noted that, for dentistry equipment, “parameters measured in the standards are often not predictors of clinical performance”, and often lacked clinical backing. For the case of the ‘syngina test’, Vostral (2017) discusses the issue that the test is merely a very coarse approximation of a menstruating human body. In the case of developing novel products in new contexts, using existing standards to develop testing programmes has limitations. It can be that the new product performs a common function in a novel way, and an established standard does not account for this. For example, developers of a novel toilet with a mechanical flush cannot rely on testing procedures outlined in standards for common porcelain flush toilets. Similarly, it can occur that an established technology is applied in a new context that is not covered by standardised tests. In these instances, new tests and performance values will have to be developed. Narayanan and Chen (2012) discuss the fact that in the early stages of competing similar technologies, the setting of a standard can result in a “winner-take-all outcome”, as seen in the competition between Betamax and VHS video systems. Moreover, Hu (2010) lists potential threats that international standards could pose to innovation, such as exclusion of innovative start-ups from the market and lack of incentive for leading companies to innovate beyond a minimum-standard level of quality, but also mentions that the benefits of standards toward innovation outweigh the limitations.

The ISO 30500 Standard

The attempt to assist innovation through standards can be applied to the development of sanitation technologies as well: the 'International Organization for Standardization' (ISO) recently published the standard *ISO 30500:2018 Non-sewered sanitation systems*. It "specifies general safety and performance requirements for design and testing as well as sustainability considerations for non-sewered sanitation systems", and thus aims "to support the development of stand-alone sanitation systems […] and promote economic, social, and environmental sustainability […] " (ISO, 2018). In the document, requirements for performance, materials, safety, maintenance, and sustainability are listed and testing procedures are described in great detail. The 'Annex A – Test methods and additional testing requirements' comprises 33 pages, and the main document 34. The range of tests covers a comprehensive list of aspects concerning the safety, quality, and usability of non-sewered sanitation systems, but does not necessarily account for the statistical variation in measurements, as would be considered in DOE. For example, only one unit of a new sanitation system is to be tested for the ISO 30500 standard. Similarly, the standard does not fully support a UCD approach. While the ease and safety of use are described as requirements, and consideration is given for variations in cultural requirements like the distinction between users preferring the squatting or seating positions, the standard cannot account for the broad variety of user preferences according to their physical, cultural, and social needs. Such considerations are given in UCD.

3.4.7 Usability testing and User Centred Design

The term 'User Centred Design' (UCD), first coined and publicised by Norman and Draper (1986) in the context of software design, encompasses a collection of processes and methodologies that follow the basic principles of a human-centred approach, which are now described in the international standard ISO 9241-210:2010 (ISO, 2010):

- *The design is based upon an explicit understanding of users, tasks and environments.*
- ➔ Identify all relevant stakeholders, their needs, and the context of use, i.e. the characteristics of users, tasks, and environment.
- *Users are involved throughout design and development.*
- ➔ Users are an important source of information about context of use. The participants should reflect the target users' (range of) characteristics. The type and magnitude of participation will likely change throughout the development process.
- *The design is driven and refined by user-centred evaluation.*
- ➔ Gather user feedback on designs, e.g. prototypes, to detect unknown challenges or requirements. The final product can similarly be tested to ensure the UCD was a success. Long-term issues can be uncovered through user feedback after market-release.
- *The process is iterative.*
- ➔ As described above, repeating certain steps of the design process while building on the learnings of the previous repetition is widely accepted as a successful method of progressively improving the design (Wynn and Eckert, 2017).
- *The design addresses the whole user experience.*
- ➔ The user experience is influenced by the technology's functionality, performance, and user interface, as well as the user's individual characteristics, skills, and previous knowledge. To improve it, all these factors need to be considered, and the user-technology interaction should be adjusted accordingly.
- *The design team includes multidisciplinary skills and perspectives.*
- ➔ While the interdisciplinary, and often international, nature of teams collaborating on PD projects can be the cause of conflict initially (Yim *et al.*, 2014), it is widely accepted that the combined knowledge and skillset

of multidisciplinary teams are beneficial to their success (Edmondson and Nembhard, 2009).

Usability testing is only one, albeit essential, part of the entire UCD process (Bastien, 2010), and comprises in itself a range of possible tests: from complex experimental designs as produced with DOE methods and involving large numbers of participants to rather informal tests with a single potential user as participant. Considering the aim of such testing is often to obtain qualitative information for the design process, rather than obtaining statistically relevant design parameter values, less formalised, qualitative methods are the focus of Rubin and Chisnell's (2008) 'Handbook of Usability Testing'. While there are cases of user tests designed using DOE principles (e.g. Jensen *et al.*, 2018), these remain the exception, as the more common approach for user tests seems to be a qualitative one (Bastien, 2010) .

Usability testing and UCD appear to be particularly important for products that have a high degree of complexity but are used by a broad spectrum of users, with varying degrees of expertise, for example a tubeless insulin pump (Pillalamarri, Huyett and Abdel-Malek, 2018). Another application would be for products specialised for a certain user group, like a motorcycle tool for one-handed users (Sudin, 2013). However, a large portion of usability tests is still conducted in software development, for example for a drill rig control system (Koli *et al.*, 2014).

3.4.8 Distinction between front end and back end – lessons from software development

For the case of the NMT, a distinction between the toilet seat, bowl, and flush, i.e. the "user interface" or front end, and the treatment system, or back end, can be made. This is analogous to software products like web sites (Chen and Iyengar, 2003). The front end and back end of a system require different testing in the PD process (Sneed, 2004; Bertolino, 2007; Sánchez Guinea, Nain and Le Traon, 2016). For example, while the front end is the part of the product with which the users will interact, the back end is usually only of indirect concern for them, as long as everything operates as expected. Hence, the front end should undergo user testing early on (Chuang, Shih and Hung, 2011), while the back end might only require limited user testing at later stages, to ensure maintainability by trained personnel. On the other hand, the back end of the NMT will likely require more extensive laboratory testing than the front end, as the treatment processes are more complicated than the user interface.

It might therefore be sensible to consider testing for the front end and back end independently, and in a separate step actualise integration testing of the individual components.

3.4.9 Visualisations of PD processes

As mentioned above, visualisations can be beneficial for product developers to plan and communicate their work (Keller *et al.*, 2006). Wynn and Clarkson (2018) give a very comprehensive overview of a large body of work on process models in PD, including visualisations thereof. They categorise models focusing “on the large-scale organisation and management of design and development” as macro-level models. Examples of these are well-known models such as the Stage-Gate model (Cooper, 1990), the V-model (Forsberg, Mooz and Cotterman, 2005), the Waterfall model (Royce, 1970), and the Spiral model (Boehm, 1988). While all these models differ in their philosophy, reflected in the shape of their visualisations, they have some common characteristics: They all describe a continuously progressing process towards the final product, and while they all mention testing at some point in this process, they do not seem to consider testing throughout its entirety. Generally, the importance of the role that testing plays in the various models reviewed by Wynn and Clarkson (2018) is not reflected in their visualisations. This further emphasizes the importance of developing a visualisation of testing activities in PD, not just for the NMT.

As the NMT project does not follow a specific PD process model, a visual description of the testing activities could conceivably be shaped in a number of ways. However, for the sake of simplicity, it seems sensible to base it on the progression of the project to date. Recently, two teams worked on designing and testing the NMT’s front end, and two teams were allocated to researching, developing, and testing the back end membrane and combustion processes respectively. As described in the previous section, a separation into parallel testing activities for front end and back end seems sensible. Furthermore, the entire process has progressed steadily, and even though iteration occurred, a linear model describes the overall development most aptly.

The end point of many models is the launch, or deployment, of the product, although some consider also the operation and maintenance of the product (Wynn and Clarkson, 2018). For the case of the NMT, the envisioned final test of a prototype, one which is practically identical to the final product, is envisioned to be the testing for compliance with the ISO 30500 standard, conducted by a licensed laboratory. Therefore, this test would signify the endpoint of a visualisation of the NMT testing strategy.

3.4.10 Summary

A testing tool for the development of a novel sanitation system should consider all aspects to provide a comprehensive overview of the considerations that need to be made when planning prototype tests. We believe that a combination of existing concepts – not only in testing – is a common occurrence in PD. An example is Lean Six Sigma, a now established concept itself, which combines the two management methodologies ‘Lean’ – a methodology to “remove non-value activities from the [PD] process” and ‘Six Sigma’ – a methodology to reduce variability and thus defects and errors in the process of concern (Alexander, Antony and Rodgers, 2019). Furthermore, since the dawn of computer aided engineering, a combination of virtual and physical testing has been (Auweraer and Leuridan, 2005) and continues to be promoted by experts (Tahera, Earl and Eckert, 2014). Likewise, the testing practice in private enterprises is likely to be more experience-based and will often combine various concepts to varying degrees. However, a visualised combination of different aspects appears to be a novel conclusion.

To incorporate all discussed aspects, a tool for testing of prototypes in PD should thus:

- Have a visualised form,

- Consider different types of tests, for example user tests, laboratory tests, field tests, and international standard tests,
- Consider different phases of the PD process (e.g. *exploration phase, assessment phase, and validation/verification phase*), and how the knowledge sought by prototype tests changes in each phase,
- Consider iteration as a possibility throughout the PD process, while indicating that the decision to iterate is based on many factors,
- Consider front end and back end testing as distinct activities,
- Consider usability testing, and follow UCD principles, particularly in the development of the front end,
- Consider the use of standard compliance tests and standard requirements as benchmark for performance and safety,
- Consider the use of ALT and HALT methodology to identify weak points and estimate the product's reliability and durability, and
- Consider the use of DOE-principles where possible to ensure statistical validity and efficient use of time and resources.

3.4.11 Synthesis: A Visual test planning tool

Derived from the considerations described above, a visual test planning tool for the NMT could look like the flow chart shown in Figure 3-3, with the additional legends in Figure 3-4.

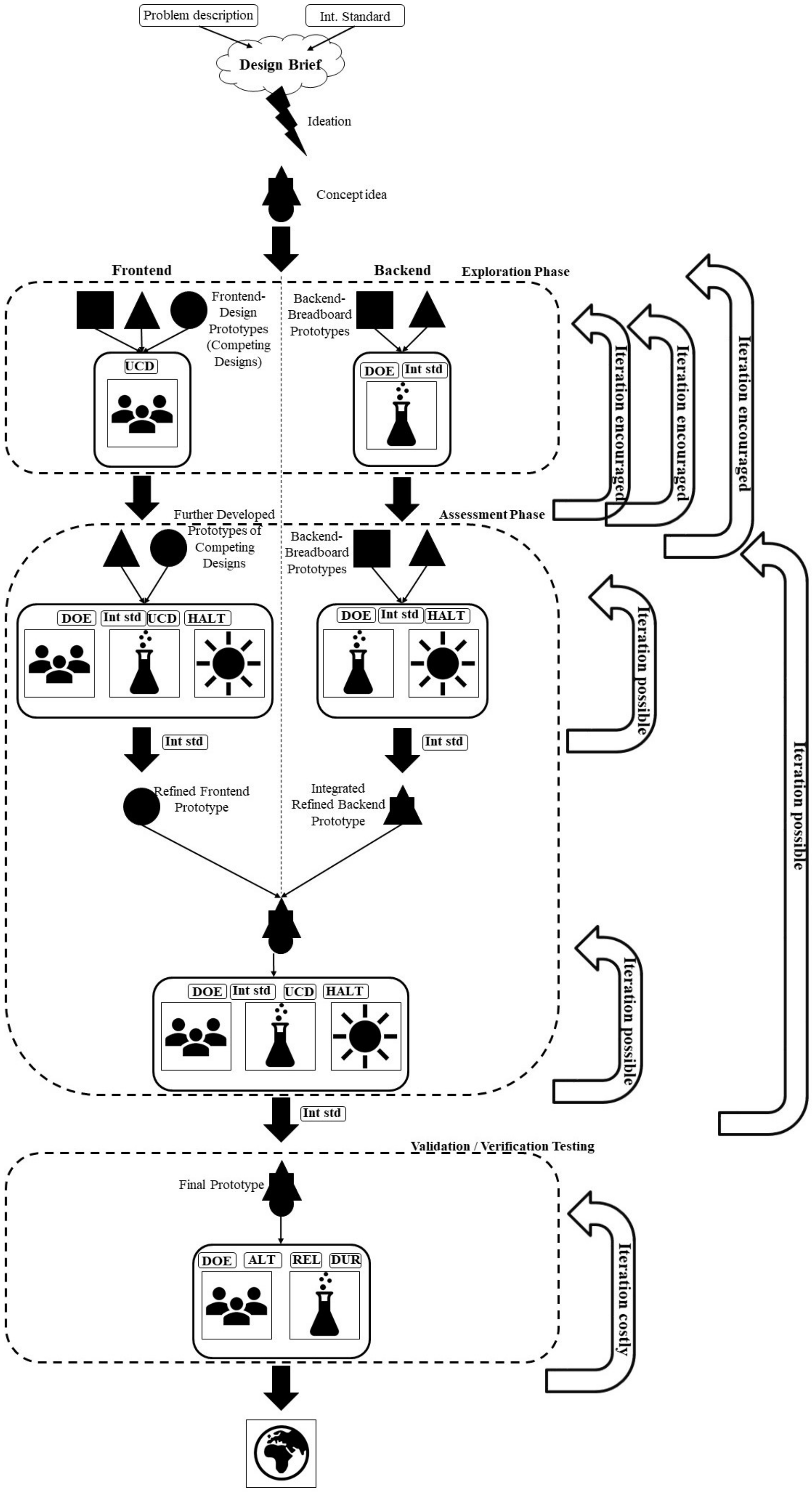
Problem description
Int. Standard
Design Brief
Ideation
Concept idea
Frontend
Backend
Exploration Phase
Frontend-Design Prototypes (Competing Designs)
Backend-Breadboard Prototypes
UCD
DOE
Int std
Iteration encouraged
Iteration encouraged
Iteration encouraged
Assessment Phase
Further Developed Prototypes of Competing Designs
Backend-Breadboard Prototypes
DOE
Int std
UCD
HALT
DOE
Int std
HALT
Iteration possible
Iteration possible
Int std
Int std
Refined Frontend Prototype
Integrated Refined Backend Prototype
DOE
Int std
UCD
HALT
Iteration possible
Int std
Validation / Verification Testing
Final Prototype
DOE
ALT
REL
DUR
Iteration costly

Figure 3-3: Visual test planning tool. A simple linear PD process model was chosen, divided into the three phases exploration, assessment, and validation/verification, with parallel strands of testing for the front end and back end, considering different types of testing, DOE, usability testing, reliability/durability testing, and international standards at different stages of the process, and possible iteration loops throughout the process. As value over cost per iteration decreases with product maturity, iteration loops are marked as *encouraged, possible,* and *costly* over the course of the three phases.

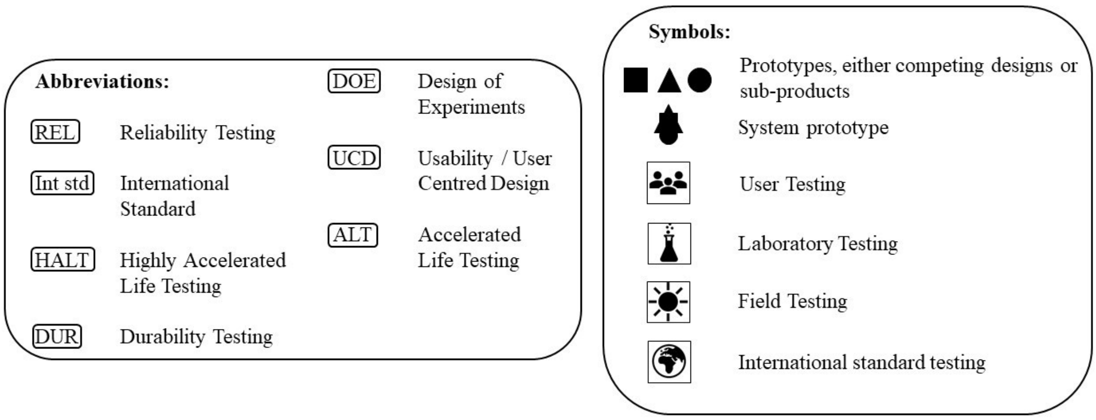

Figure 3-4: Legends for symbols and abbreviations in Figure 3-3

Starting from the problem description, and potentially using input from already existing international standards, a design brief is the first step of the PD process. This will prompt first concept ideas, thus beginning the exploration phase. Designers will then develop potential solutions to the problem, which will be realised in the first prototypes, both for the front end and back end. The front-end prototypes will often have low functionality and are mainly used to communicate the designers' vision. They can then be tested with potential users, to assess whether the designers are 'on the right track', and their proposed solutions could be accepted by users. The back-end prototypes will likely be first simple prototypes of single components, to prove the viability of the concept ideas. Several competing designs might be tested simultaneously, and iteratively, to refine the initial designs. In this phase, more iterations should be encouraged, as producing and testing prototypes is relatively cheap and yields a lot of useful information.

In the following assessment phase, further developed prototypes can be constructed. These might be prototypes of sub-products or the whole product, and they are likely to already have a certain degree of functionality. It is on these prototypes, and increasingly developed iterations thereof, that a variety of tests will be conducted to learn about the technical, functional, and aesthetic aspects of the NMT. Using DOE and UCD methods, and tests from international standards as benchmarks, components and (sub)systems are tested in laboratories and field tests towards functionality and usability. HALT methods can be used to identify and mitigate likely failure points. While first tests will still be conducted on separate prototypes for the front and back end, user tests and functionality tests can be conducted simultaneously at later stages of sub-product maturity, when an integrated prototype is constructed. Several iterations are possible, until satisfactory component and system maturity is reached, and competing designs can be developed and tested simultaneously. It can be a difficult decision to define a cut-off point for further iterations. The developer has to have confidence that the entire system will safely function as intended. The minimum performance values of an international standard can provide helpful guidance to ensure this confidence.

In the final phase of validation and verification, a finalised design, maybe already produced on the product’s assembly line, is tested for reliability and durability using ALT methods. DOE methods can be applied to improve statistical validity of tests. Final user tests ensure all user-related problems have been mitigated. If no serious problems arise, the product can be sent to be tested towards compliance with an international standard. In the case of the NMT, this would be the standard *ISO 30500:2018 Non-sewered sanitation systems*.

There is a possibility that tests reveal problems which necessitate a return to much earlier stages of the PD process. However, this should be avoided by completing an appropriate number of test iterations during the exploration and assessment phases, as it would entail significant cost to iterate at such a late stage.

3.5 Discussion

The visual test planning tool presented in Figure 3-3 and Figure 3-4 gives an overview of the considerations to be made for planning and communicating testing efforts during the development process of the NMT. Tahera et al. (2015) stress the importance of testing in the PD process, and there is abundant research on the ideal number and timing of tests within PD (for example Thomke and Bell, 2001; Al Kindi and Abbas, 2010). However, there is a lack of publications focusing on how to plan and communicate testing throughout the PD process, which is attempted here.

The flow chart aims to combine several aspects of testing prototypes that, in their own field, are well-developed concepts with numerous publications and ongoing research on refining and advancing methods. It would be beyond the scope of this paper to attempt to outline more detailed descriptions of all aspects, and we therefore refer to the referenced literature for such information. Rather than supplying users of the flow chart with such detailed information, its function is intended to be that of a suggestion of considerations to be made, in the form of a holistic overview. While it reflects the processes followed in the development of the NMT, the tool is not built on the first-hand expertise of PD practitioners, but rather on academic literature. A step towards generalisation would be to consider such first-hand knowledge.

The testing tool can be applied to visualise and plan testing efforts for the NMT components and the overall system. It can also be used to communicate these testing efforts among and between teams and people new to the project. Having a holistic overview of the nuances of prototype testing may result in more statistically valid or more useful data. Also, using the tool to communicate the various testing efforts amongst teams could aid in coordinating testing to further enhance the value of obtained results. At this stage, the proposed flow chart has not been applied to plan or communicate testing efforts in the NMT project.

Ongoing work aims to test its application in the development of the NMT, which will serve as case study for refining the tool.

Additionally, its generalisation to be used in a variety of PD projects is part of an ongoing qualitative study which seeks to collect knowledge of experts in the field of prototype testing, in order to develop a more universally applicable version of the tool. The presented version is based on existing academic literature, but a lot of expertise about testing in PD remains in the realm of (anecdotal) knowledge of engineering practice (Tahera *et al.*, 2019). Therefore, we invite readers with expertise in these fields to complement the above-mentioned study by commenting either on this article directly or by contacting the corresponding author.

A generalised, refined version of the flow chart tool could benefit multiple groups of practitioners in PD. For example, test engineers may be able to better design tests and testing rigs with the entire PD process in mind. Project managers, designers, and test engineers can better communicate about tests, timelines, and requirements with a visual aid (Keller *et al.*, 2006), and designers could develop more appropriate prototypes that are tailored to the planned tests. An important aspect to consider in a generalised version would have to be the use of virtual prototypes, which take an ever-increasingly important role in PD (Tahera, Eckert and Earl, 2015). Given the multitude of PD process models in use (Wynn and Clarkson, 2018), it is likely that there could not be a single generally applicable flow chart, but rather a modular version that can be adjusted to fit any given company's processes.

3.6 Conclusion

This paper presents a visual tool to aid in planning and communicating prototype testing efforts for the case of the Nano Membrane Toilet, a complex novel sanitation technology. The tool, a flow chart depicting various aspects of prototype testing throughout the PD process, was developed by collating information about prominently featured aspects of prototype testing in the academic literature.

As the tool is still untested, its validity is not yet confirmed. Ongoing prototype tests that are planned using a previous version of the tool will form the basis of an initial case study. However, an empirical validation of the tool seems unlikely, given the uniqueness of most PD processes. Instead, a qualitative approach collecting and analysing expert knowledge could be a solution toward refinement of the tool.

Much like a product in development, the presented tool will have to undergo more iterations to improve its robustness and its utility. We are currently making steps toward this aim. Nevertheless, we believe that the presented form of the tool, based on a multitude of academic publications, already has value to practitioners in prototype testing and will find use in the development of the NMT.

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4 Faeces – Urine separation via settling and displacement: prototype tests for the Nano Membrane Toilet

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4.1 Abstract

The development of novel, non-sewered sanitation systems like the Nano Membrane Toilet requires thorough investigation of processes that may seem well-understood. For example, the separation of solids from liquids in a small-volume container at the scale of a household toilet has not been studied before. In two sets of experiments, the settling of real faeces and toilet paper in settling columns and the settling of synthetic faeces in a conical tank are investigated to understand the factors affecting the liquid quality for downstream treatment processes of the Nano Membrane Toilet. Toilet paper is found to be the major inhibitor to settling of solids. While a lower overflow point results in better phase separation through displacement, a higher liquid volume and frequent removal of solids may be more advantageous for the liquid quality.

Keywords: *Prototyping, testing, DOE*

Abbreviations: ANOVA – Analysis of Variance; COD – Chemical Oxygen Demand; dCOD – dissolved Chemical Oxygen Demand; DOE – Design of Experiments; F – Frequency (of defecation); NMT – Nano Membrane Toilet; TP – Toilet Paper; TS – Total Solids; UDDT – Urine Diversion Dehydration Toilet; V – (Tank) Volume; VS – Volatile Solids

4.2 Introduction

In an effort to develop a safe, waterless, non-sewered sanitation technology, Cranfield University is developing the Nano Membrane Toilet (NMT) (Parker, 2014): a novel product that comprises a waterless mechanical flush that receives faecal waste and toilet paper and transports it into a conical collection tank with about 10 l volume underneath the toilet bowl, membrane treatment of liquid waste, and transport of solid waste via auger, followed by drying and combustion. Heat from the combustion is recovered to power the membrane process. The Flush, membrane and combustion processes have been developed and tested to work individually (Onabanjo, Kolios, *et al.*, 2016; Kamranvand *et al.*, 2018; Hennigs, Ravndal, *et al.*, 2019), while transport and dewatering of solids via auger are still under investigation. Existing solutions of separating liquids from solids at the source, so-called urine diversion dehydration toilets (UDDT), have been shown to be problematic for users (Roma *et al.*, 2013; Mkhize *et al.*, 2017), and field trials of the mechanical flush revealed that users of UDDT preferred the flush over their usual toilets (Hennigs, Ravndal, *et al.*, 2019). Similarly, other studies reported problems with using, operating, and maintaining urine diversion toilets (Lienert and Larsen, 2010; Blume and Winker, 2011; Uddin *et al.*, 2014). Therefore, a combined collection of liquids and solids is the desired mode of operation in the NMT's mechanical flush. This requires phase separation before both waste streams can be introduced to their respective treatment processes. With better separation of liquid from solid waste streams, the performance of the membrane treatment processes would likely be increased (Sun and Leiknes, 2012; Kamranvand *et al.*, 2018), as would be the amount of heat to be recovered from the combustion (Onabanjo, Patchigolla, *et al.*, 2016). While the research into the transport of solids via auger includes dewatering in the auger, and while it might become apparent that a certain amount of liquid is required for the auger to perform optimally, we expect that solid-liquid separation will have to occur mainly in the NMT's collection tank. In the original concept design of the NMT, this separation was intended to be achieved by settling of solids. Preliminary investigations of settling behaviour of faeces in water showed that even those faeces that initially floated eventually sank (Cruddas *et al.*, 2015). This was explained by the fact that those faeces that float do so because of their gas content (Levitt and Duane, 1972), and once the gas exited the faeces, they would settle. However, during field tests in South Africa, in which real faeces, urine, and toilet paper where collected in a prototype of the collection tank, settling did not seem to occur (unpublished results). This was a significant observation, as it challenged a fundamental expectation of how the NMT would operate. Since the prototype used in these field tests was not transparent, the actual settling behaviour of faeces and toilet paper in urine could not be observed. Unfortunately, there is no literature describing sufficiently similar settling processes. Gravity settling and thickening are well-understood processes in treatment of wastewater (Metcalf & Eddy Inc. *et al.*, 2014) and faecal sludge (Dodane and Bassan, 2014) but the influent of settling tanks of municipal scale is vastly different from the fresh urine, faeces, and toilet paper in a small volume container. At the time at which wastewater or faecal sludge reach treatment facilities, toilet paper and faeces have disintegrated into much smaller particles due to the mechanical effects of transport through a sewer network and / or pumping, creating a more homogenous slurry or sludge (Eren and Karadagli, 2012; Niwagaba, Mbéguéré and Strande, 2014) than the contents of the NMT's collection tank. Thus, calculations for the design of settling tanks are based on small, ideally spherical particles (Bassan, Dodane and Strande, 2014), and on solids content measurements in *Imhoff cones*, for which coarse materials are usually removed (Metcalf & Eddy Inc. *et al.*, 2014). In contrast, toilet paper and faeces in the NMT collection tank appeared to be mainly still intact. Even the settling processes in septic tanks – potentially the closest analogue to the NMT's collection tank – are rarely the object of academic research. In one recent example, Dos Santos *et al.* (2017) describe an improvement of the classic septic tank to enhance settling. General guidance about septic tanks just assumes settling of solids, but does not appear to be investigated thoroughly (Oxfam, 2008; Tilley *et al.*, 2014).

The observations in the field prompted the idea to achieve phase separation by settling and displacement, rather than settling alone: With a lower overflow point, a higher ratio of solids to liquids would be promoted. As new solids are introduced, liquids are expected to overflow out of the tank (Figure 4-1). To test the practicability of this concept for the NMT, the effectiveness of phase separation by displacement would have to be investigated in a tank with a similar (conical) geometry to that of the NMT collection tank. The conical shape of the tank was chosen as the sloped walls promote settling-thickening, which is the reason municipal thickeners and *Imhoff tanks* often take this shape (Dodane and Bassan, 2014; Metcalf & Eddy Inc. *et al.*, 2014).

The effectiveness of solid-liquid separation can not only be gauged by the visual observation of less liquid in the tank, but also in the quality of the overflowing liquid: a higher pollution of small solids particles and soluble organic compounds in the overflowing liquid would negatively affect the downstream membrane treatment processes (Kamranvand *et al.*, 2018). To gauge the concentration of particles and organic compounds, Total Solids (TS) and Chemical Oxygen Demand (COD) can be measured, respectively (Metcalf & Eddy Inc. *et al.*, 2014).

This study investigates the settling of fresh faeces and toilet paper in urine, and whether a lower liquid overflow level promotes solid-liquid separation within small volume settling columns. Furthermore, the study investigates the factors influencing solid-liquid separation by settling and displacement in a conical prototype collection tank for the Nano Membrane Toilet.

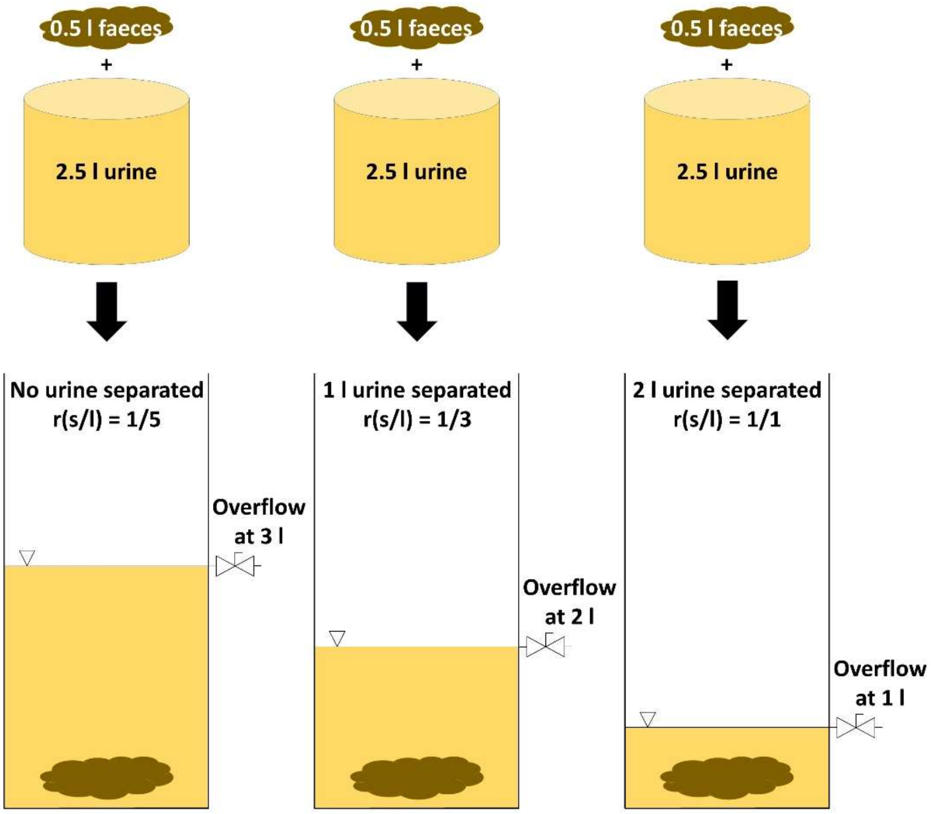


Figure 4-1: Solid-liquid separation through displacement: the lower the liquid overflow point of the collection tank, the more urine is separated through displacement by exiting through the overflow. This promotes a higher solids-to-liquids ratio.

4.3 Materials and Methodology

4.3.1 Tests in settling column

Following the observations during previous field tests, the settling behaviour of faeces was investigated in settling tests in transparent columns (Figure 4-2), using real faeces and urine, with the addition of toilet paper. Urine and faeces samples were anonymous donations collected from users of the office toilets at Cranfield Water Science Institute.

With an inner diameter of 177 mm and a height of 377 mm, the columns have a maximum volume of 9.28 litres. The columns have four sampling ports to draw liquid samples at 70, 140, 210, and 280 mm height respectively. The ports were numbered P1 – P4 from lowest to highest.

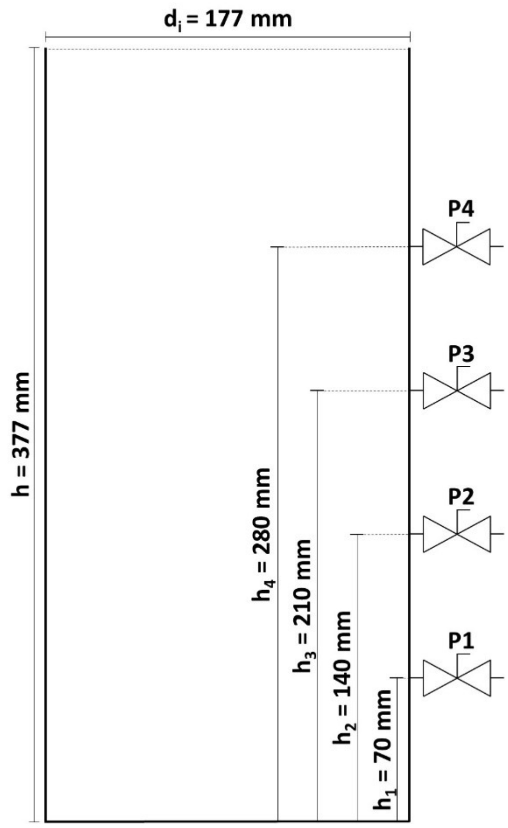


Figure 4-2: Schematic of transparent settling columns used in real-faeces tests.

Simulating the use of the NMT by several people, three columns were filled with fresh urine, faeces, and toilet paper consecutively, over the course of five days for the first two columns and four days for the third. The numbers of simulated urinations and defecations, and their timing, were subject to the time and numbers of donations of fresh faeces and urine, but it was attempted to maintain a ratio of 3 urination events per 1 defecation event, with peak times in the early morning and early afternoon hours. On average, a single defecation weighed 120.3 g, and a single urination averaged 125.8 g. The considerations of time and weight of toilet uses were based on data gathered by Cranfield researchers (Cruddas *et al.*, 2015). The numbers of defecation and urination events during a given hour for each day of the three column tests are listed in Table 4-1. Figure 4-3 shows the average daily toilet use events simulated over the course of a day for all columns. To investigate whether displacement of urine could improve solid-liquid separation, the liquid-overflow points for the three columns were set at different heights: For the first column test (**C1**), the highest sampling port (**P4**) remained open and thus acted as an overflow. For the second column test (**C2**), the third sampling port from the bottom (**P3**) remained open, and for the third column test (**C3**) the second port from the bottom (**P2**).

Table 4-1: Number of defecations and urinations during a given hour for the three column tests.

C1				C2				C3			
Day	Hour starting at	No. of faeces	No. of urine-loads	Day	Hour starting at	No. of faeces	No. of urine-loads	Day	Hour starting at	No. of faeces	No. of urine-loads
1	07:00	2	2	1	06:00	3	3	1	07:00	1	1
	08:00		5		07:00		1		08:00	2	2
	11:00		7		08:00	2	5		10:00	1	4
	13:00	1	2		11:00		2		11:00		6
	15:00		1		12:00	2	4		13:00	1	2
2	07:00	3	6		14:00	1	9	2	07:00	2	6
	08:00	1	3	2	07:00	2	6		10:00		2
	09:00		2		10:00	3	4		12:00	2	3
	10:00	1	3		13:00	1	8		13:00	1	3
	11:00	1	1	3	08:00	2	6	3	07:00	2	4
	12:00		3		12:00	1	5		08:00		2
	15:00		1		13:00	1	2		10:00		1
3	07:00	2	4	4	07:00	3	9		12:00	2	4
	11:00	1	3		08:00		1		13:00		1
	13:00	1	3		12:00	1	2	4	07:00	2	3
	15:00	1	2		13:00		1		08:00		3
4	07:00	1	1	5	07:00	2	2		09:00		1
	08:00		2		08:00	1	5		11:00	1	2
	12:00	3	6		10:00		4				
	13:00		4		12:00	2	4				
5	06:00	1	2								

C1				C2				C3			
Day	**Hour starting at**	**No. of faeces**	**No. of urine-loads**	**Day**	**Hour starting at**	**No. of faeces**	**No. of urine-loads**	**Day**	**Hour starting at**	**No. of faeces**	**No. of urine-loads**
	08:00		2								
	10:00		2								
	11:00		1								
	12:00	2	3								

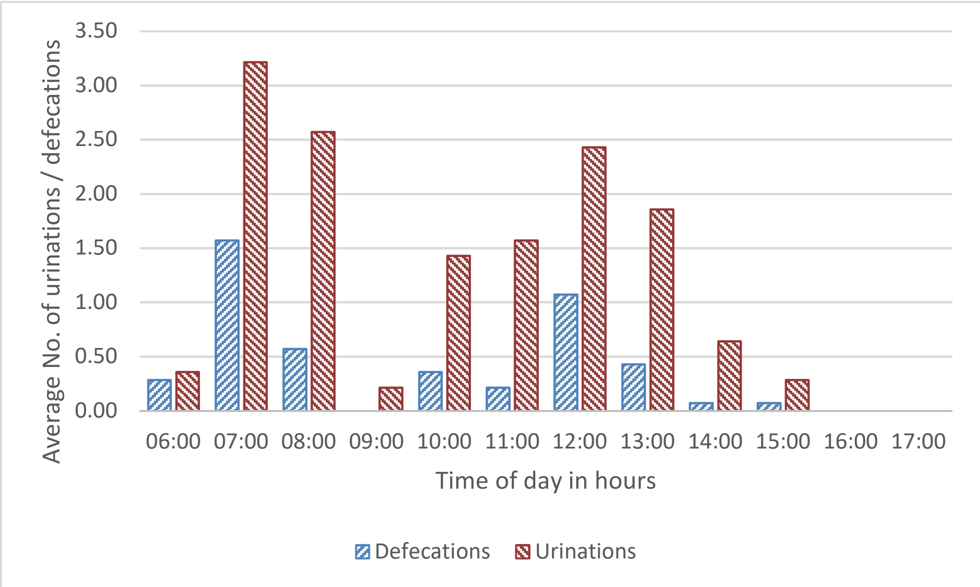


Figure 4-3: Average simulated toilet use events per day.

During the work day, at least hourly photographs were taken of the column. Liquid samples (about 30 ml each) were taken from all sampling ports below filling level three times per day. As indicators of liquid quality, COD, dissolved COD (dCOD, obtained by filtering the sample with a 450nm pore size syringe filter before analysis), TS, and volatile solids (VS) were determined for each sample, using standard methods.

4.3.2 Tests in prototype conical collection tank

To better understand the settling and displacement processes in a collection tank as it would be found in the NMT, controlled experiments using synthetic faeces in a prototype conical tank were conducted. Following a Design of Experiments

(DOE) approach (Montgomery, 2009) in order to best understand the factors influencing the overflow liquid quality, a 2^3 full factorial design was chosen.

4.3.2.1 2^3 – Factorial experimental design

Based on observations from the settling column tests, three factors were suspected to most likely have an effect on the quality of overflowing liquid: First, the size of the collection tank's **maximum liquid volume** (**V**, determined by the tank's geometry and the height of the overflow) determines the ratio of solids to liquids in the tank (Figure 4-1), and consequently the amount of liquid in contact with solids. Under the assumption that the transfer of particles and COD into the liquid is relatively independent from the solids-liquids ratio, a higher concentration of both would be expected in the liquid if less liquid is available. Thus, it would be expected that a smaller tank volume will yield a higher concentration of solids and COD in the liquid phase. Second, the **frequency with which solids are added** (**F**) was expected to affect how much time the processes within the tank are given to return from dynamic to relatively static. The more often faeces are added to the system, the more often disturbance will occur and that likely promotes transfer of small particles and COD into the liquid. The third factor under consideration was **whether or not toilet paper was added** along with the faeces (**TP**). As was already observed in previous field trials, and again in the settling column tests (see results section below), toilet paper appears to keep faeces from settling, regardless of faeces-density. The more faeces are kept in suspension, the higher the solid-liquid interface, along which particles and COD could be transferred.

Toilet paper absorbs liquid and adds to the solids-content in the tank. The tank volume limits in which space toilet paper can suspend faeces. The frequency at which faeces are added may affect settling and suspension of faeces through toilet paper. Therefore, it is conceivable that the liquid quality would also be affected by interactions of the three factors under consideration. In order to investigate all three factors as well as their interactions, a full factorial experimental design with two levels per factor was developed (Montgomery, 2009). Table 4-2 shows the eight possible combinations of levels for the three factors. The runs were carried out in triplicate, in random order. The high and low levels for the variables were set as:

- tank volume (V): low (-) = 0.7 l; high (+) = 2 l
- loading frequency (F): low (-) = 1/h; high (+) = 1/2h
- toilet paper (TP): low (-) = no toilet paper; high (+) = toilet paper added

Table 4-2: Full factorial design for liquid displacement tests. There are eight different combinations of three factors at two levels.

Combination / Factor	1	2	3	4	5	6	7	8
V	+	+	+	+	-	-	-	-
F	+	+	-	-	+	+	-	-
TP	+	-	+	-	+	-	+	-

4.3.2.2 Experimental rig

The prototype tank used for this study was designed to resemble the collection tank of the NMT (Figure 4-4). It is a conical tank with a 60° angle, which is used in standard inclined settlers (Metcalf & Eddy Inc. *et al.*, 2014), a maximum filling height of 310 mm, and five sampling ports along the side (P1 – P5 from lowest to highest). A larger valve at the bottom allowed for quick emptying of the tank. As the sampling ports are equidistant to each other on the inclining wall of a conical tank, the volume underneath the port increases exponentially with each port. If P2 is used as overflow, the maximum filling volume is 0.7 L, including the small volume below the bottom of the tank and the closed valve. If P3 is used, the maximum filling volume is 2 L.

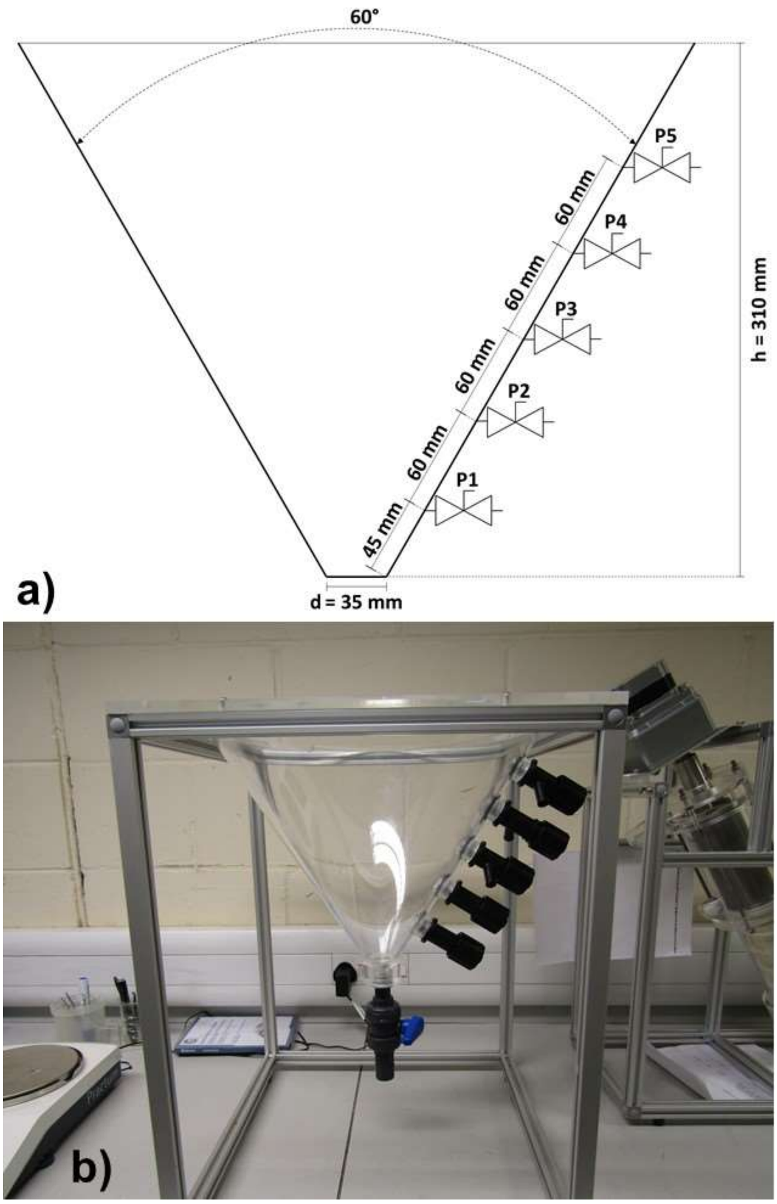


Figure 4-4: a) Technical drawing of conical collection tank; b) Photo of experimental rig with five sampling ports. Only ports two and three were used for the experiments.

4.3.2.3 Synthetic faeces

To ensure that the high variability of real faeces (Rose *et al.*, 2015) did not affect the experiment, a synthetic simulant was used instead. Penn *et al.* (2018) discuss various recipes for synthetic faeces and combine them to develop a simulant with high physical and chemical similarity to real faeces. Their recipe was amended in one aspect: Rather than oleic acid, an ingredient that was originally used by Kaba *et al.* (1990) who seem to have chosen it arbitrarily as lipid and without explaining their choice, we used peanut oil. With our decision we follow Wignarajah et al. (2006), who also used peanut oil, explaining their choice with its high content of oleic acid.

To simulate both normal stool and soft stool / diarrhoea, simulants were produced with 65% and 80% water content respectively. Both consistencies were also produced with additional baker's yeast, to produce floating stools (Figure 4-5). For the sake of simplicity, a weekly batch of synthetic faeces with 65% water content without baker's yeast was produced. From this, the four samples were created by adding water and baker's yeast as necessary. This proved less time consuming than creating four types of simulant from scratch.

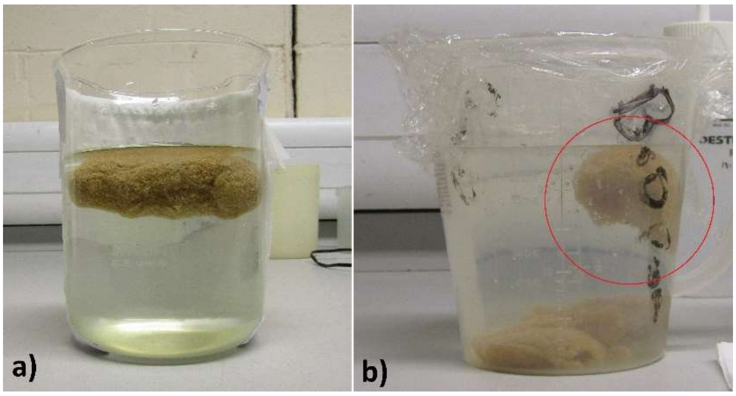


Figure 4-5: Figure 5: Floating synthetic faeces. a) with 65% water content; b) with 80% water content - only partially floating.

4.3.2.4 Experimental procedure

Before each run, the tank was cleaned thoroughly with soap and rinsed with tap water. It was then filled with tap water above the level of the sampling port used as overflow (P2 for the low-level volume, P3 for high-level volume). The port was then opened to allow the excess water to overflow, leaving the water level at exactly overflow-level. Four samples of synthetic faeces were then added to the tank, each weighing 50 g. For each run, there were two samples with 65% and 80% water content, respectively, one with and one without additional baker's yeast. The samples were added in random order, one every hour (F = 1/h), or every two hours (F = 1/2h), depending on the level set for F. If the level for TP was "+", six sheets of toilet paper were added to each faeces sample. The liquid overflowing from the open sampling port (about 30 – 50 ml) was collected and analysed for TS, COD, and dCOD. Photographs were taken of the transparent tank before and after each addition of synthetic faeces. With four liquid samples, there were four data points available for each parameter for each individual run. For each parameter and run, a linear fit of the four data points was calculated, and the slope of the fit function was used as the dependent variable in a three-way analysis of variance (ANOVA), using SPSS software. This way, the effects of V, TP, F, and their interactions could be analysed without having to consider the effect of time.

4.3.3 Ethics Statement

The methodologies used for this study were approved by the Cranfield University Research Ethics Committee (reference numbers CURES/4982/2018 CURES/2310/2017, CURES/3245/2017, & CURES/3242/2017 for the experiments using real faeces and urine in a settling column; and CURES/7913/2019 for the experiments using simulant faeces in a conical tank prototype). Donors of urine and faeces could donate anonymously and were instructed to do so only after signing a consent form, supplied to them alongside an information sheet inside the toilet cubicle.

4.4 Results

4.4.1 Settling column tests

Visual observations

All three column tests yielded the observation that the faeces – toilet paper mixture did not settle well in urine. Figure 4-6 shows the three columns at the point of solids reaching the overflow level, and large *pockets* of liquid are visible underneath the solids. It does, however, appear that eventually, a layer of faeces-toilet paper mixture covered the entire cross-sectional area of the column, creating a *plug*, preventing any liquid below from exiting. Thus, this trapped liquid could not be displaced, unlike the liquid added after the creation of the plug, which drained through the open sampling port. All sampling ports were quickly covered with solids, resulting in very slow outflow velocity. For sampling from the lower ports, a small piece of wire was poked through the port to encourage quicker outflow of liquid. Even where the sampling ports were covered by the apparent plug, liquid samples could still be collected. The open sampling port, acting as overflow point, was left untouched, and the liquid slowly drained into an adjacent container.

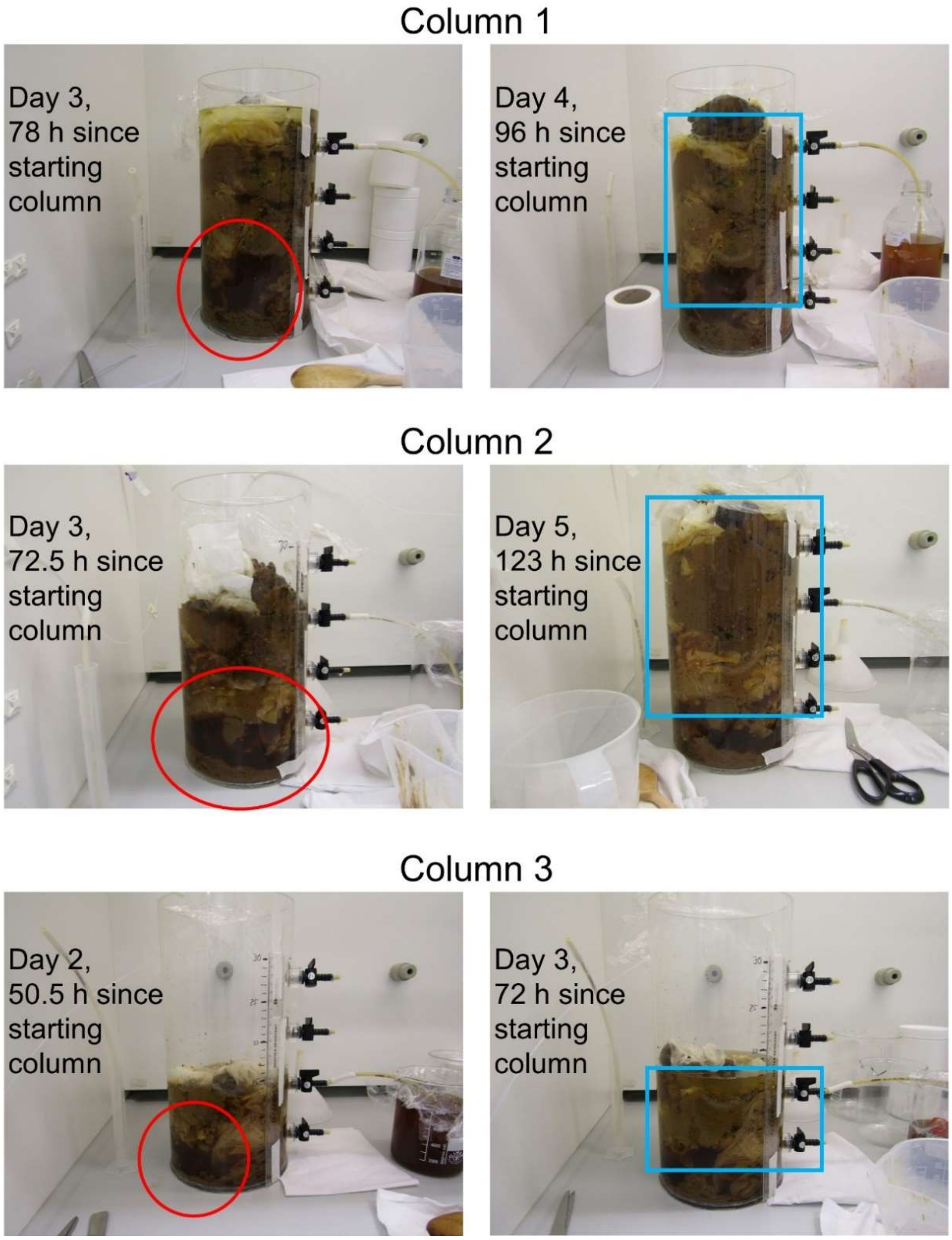


Figure 4-6: Settling columns filled with real faeces and toilet paper on the last test day respectively. All three columns show distinctly that solids did not fully settle, but rather leave "pockets" of liquid (red circles) that are eventually covered by a dense layer of faeces (blue squares).

Liquid sample measurements

Both the COD and dCOD concentrations rose steadily over time for all sampling ports (Figure 4-7). While the increase is quite steep during the first 48 hours of measurement, it appears to plateau slightly after this time. This is true for all sampling ports, meaning that the COD concentrations at a higher point of the column increase more rapidly during the first 48 hours even when the concentrations at the lower sampling ports are already plateauing (e.g. compare Figure 4-7 a) vs c)) This could be an indication of limited vertical mixing of the liquid.

Interestingly, the measured solids concentrations in the settling column experiments did not vary significantly over time, and neither did the ratio of TS to VS (Figure 4-8). This can likely be explained by the experimental procedure: In this set of experiments, both liquids and solids were continuously added to an originally empty container. When pouring liquids into the container, especially when faeces were at a higher level than liquids, small particles would be washed away and be suspended in the liquid fraction. Thus, the concentration of solids particles was quite high from the first measurement onwards. In the experiments with the conical tank, only solids were dropped into the tank initially filled with clear water. In this case, the originally very low solids content of the liquid samples rose over time (Figure 4-10).

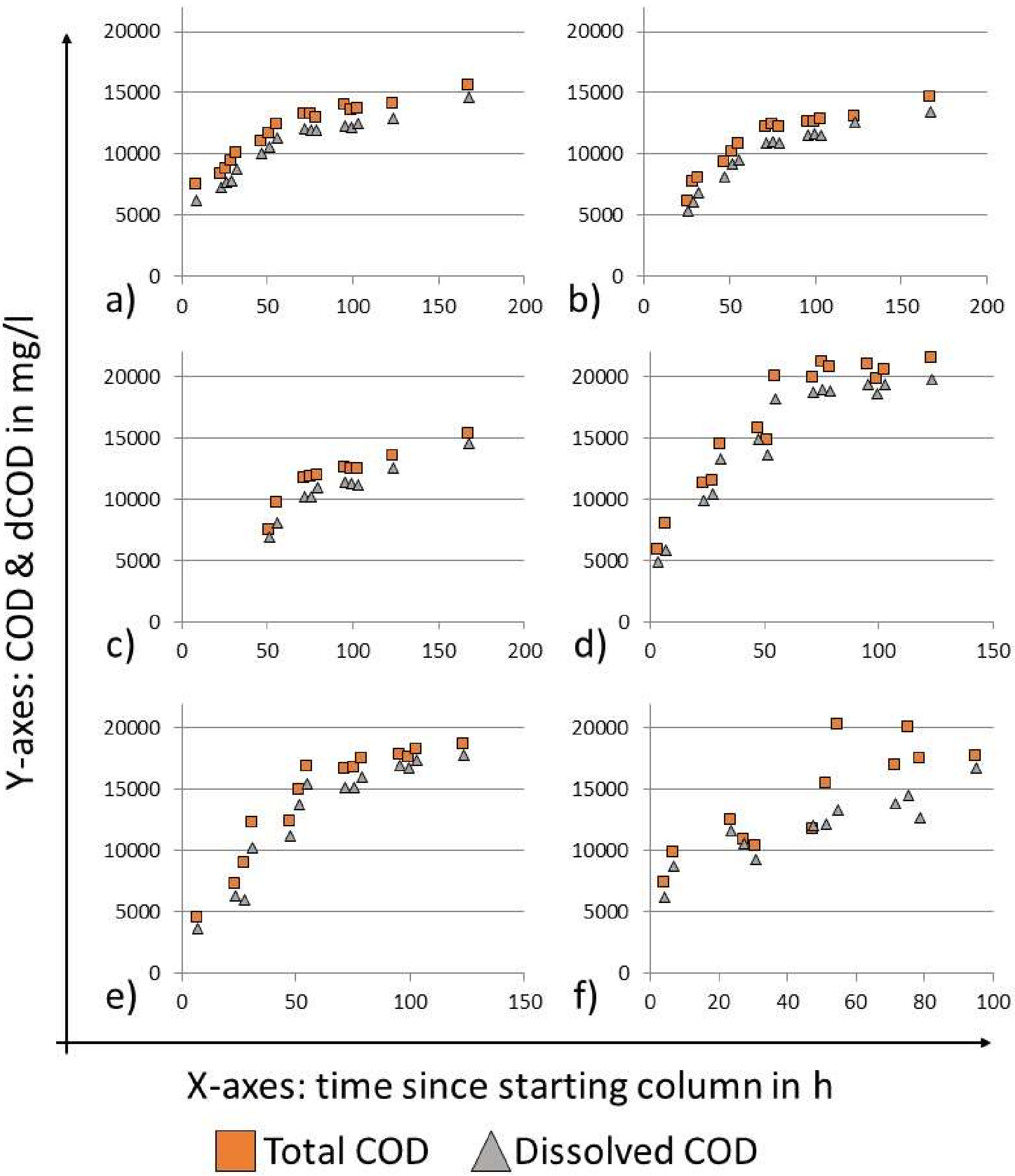


Figure 4-7: COD and dCOD measurements for settling column tests. a) C1-P1, b) C1-P2, c) C1-P3, d) C2-P1, e) C2-P2, f) C3-P1.

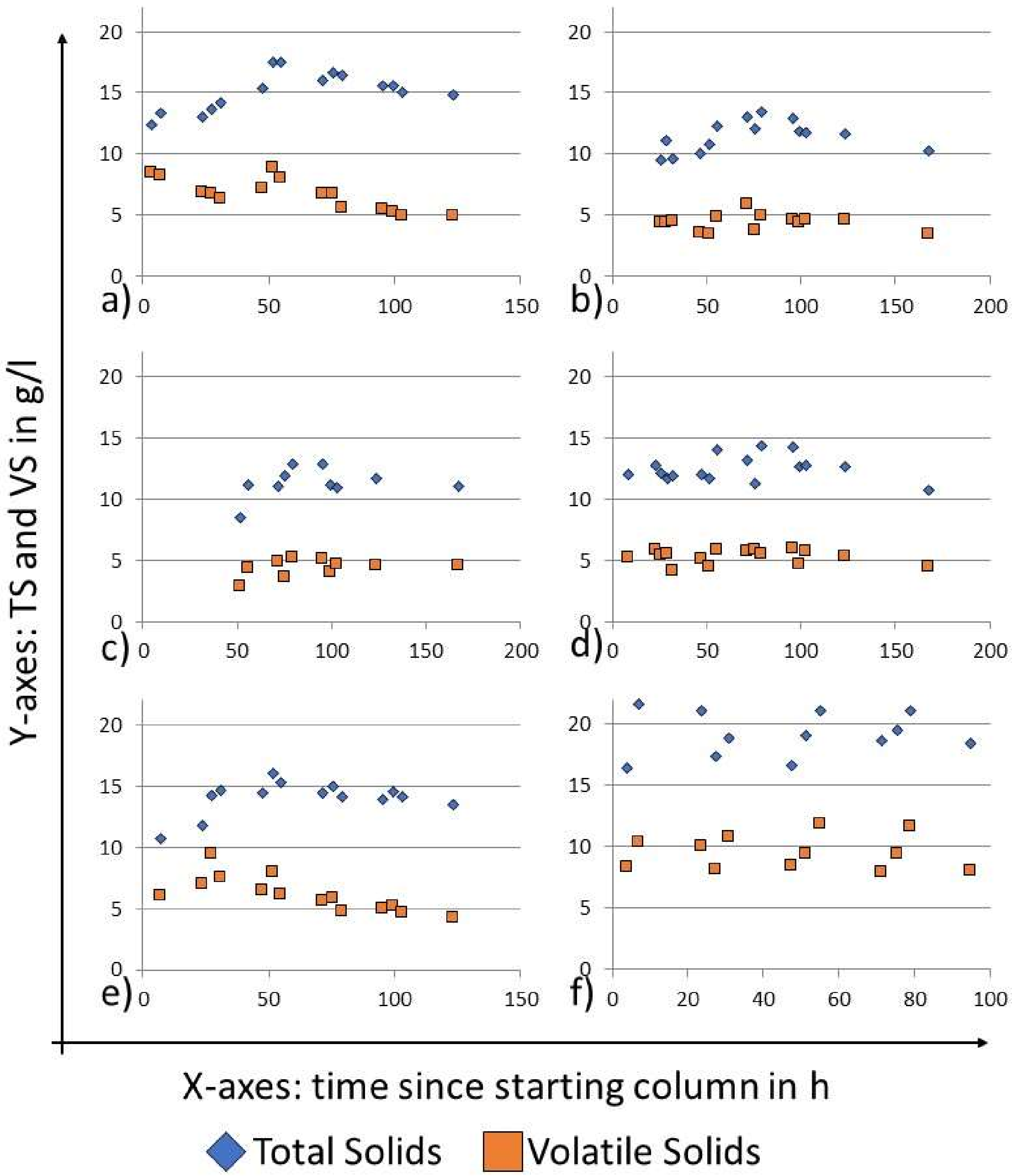


Figure 4-8: TS and VS measurements for settling column tests. a) C1-P1, b) C1-P2, c) C1-P3, d) C2-P1, e) C2-P2, f) C3-P1.

4.4.2 Tests with synthetic faeces in conical collection tank

Visual observations

Similarly to the tests using real faeces, the synthetic faeces did not settle completely in any of the experiments using toilet paper (Figure 4-9), which seemed to keep even those faeces without additional baker's yeast in suspension. Without toilet paper, only faeces containing baker's yeast floated. Left over night, these floating faeces would settle, i.e. reproducing a phenomenon in synthetic faeces previously observed in real faeces by Cruddas *et al.* (2015). For the lower volume-setting, the addition of toilet paper meant that most of the tank volume was filled by faeces and toilet paper, which absorbed a lot of liquid. Whether toilet paper was added or not, the lower volume tests resulted in a visibly higher solids to liquids ratio in the tank, and therefore better solid-liquid separation through displacement.

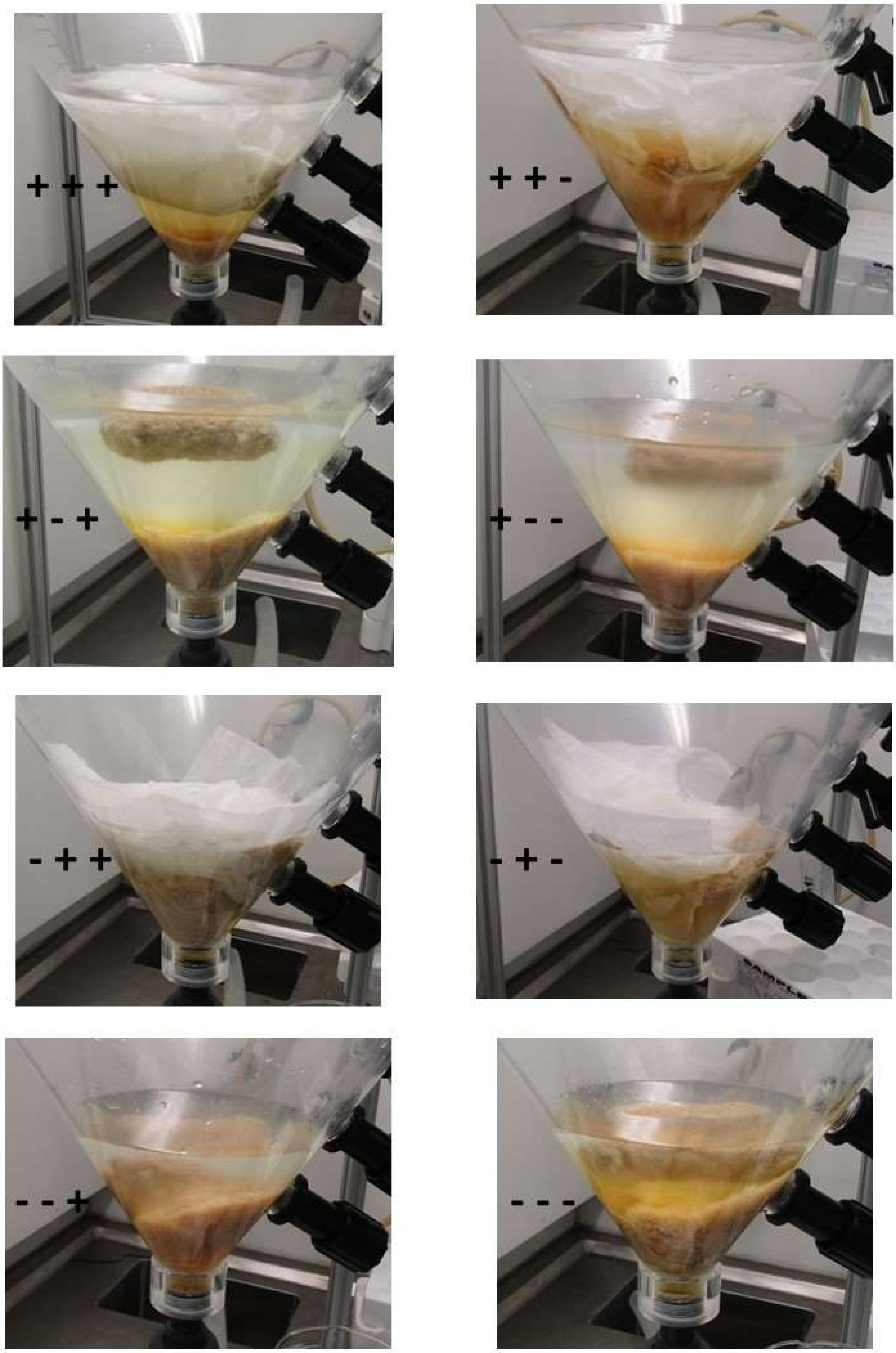


Figure 4-9: images of the prototype tank at the end of an experiment for each level setting of the three factors V, TP, and F (+ and - symbols referring to the three factors in this order).

Liquid sample measurements

TS, COD, and dCOD measurements generally rose over time (Figure 4-10, Figure 4-11, and Figure 4-12, respectively). With only four data points per experiment, any statement about the shape of the trend would be speculative. For the purposes of the statistical analysis, the trends were considered linear within the investigated range.

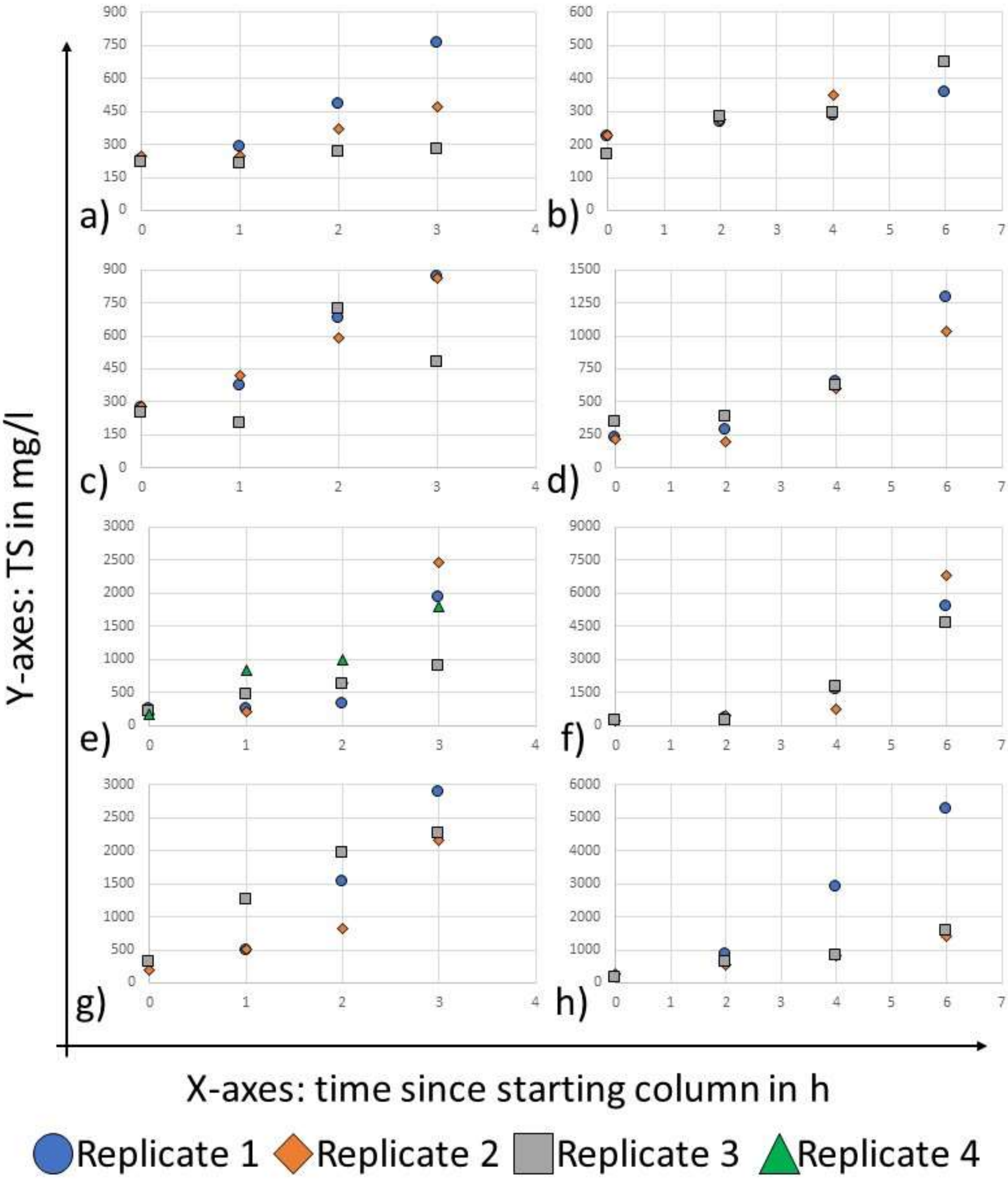


Figure 4-10: TS measurements for conical tank tests. a) +++, b) ++-, c) +-+, d) +--, e) -++, f) -+-, g) --+, h) ---. Note the varying scales on the y-axes, made necessary to depict the trends.

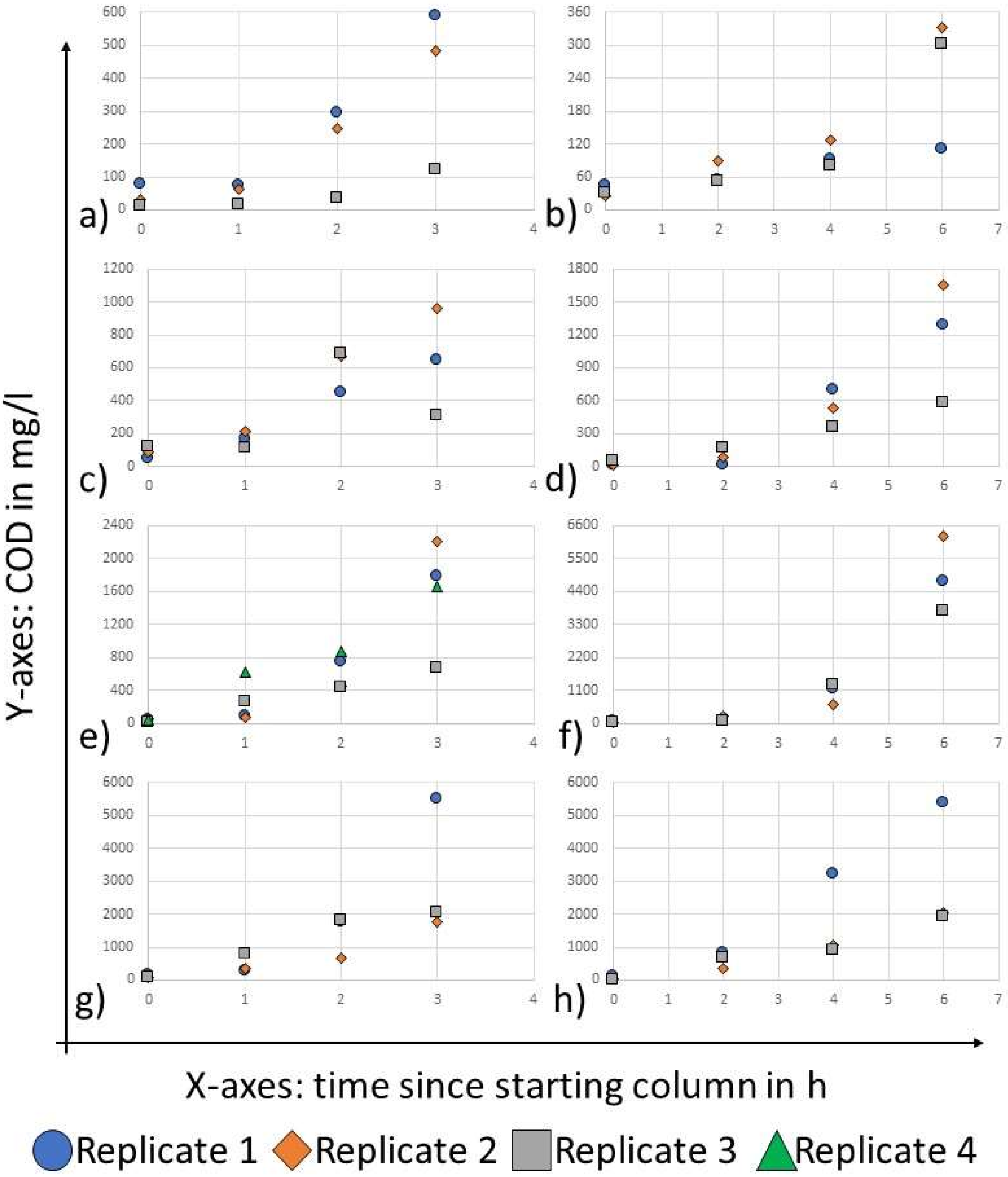


Figure 4-11: COD measurements for conical tank tests. a) +++, b) ++-, c) +-+, d) +--, e) -++, f) -+-, g) --+, h) ---. Note the varying scales on the y-axes, made necessary to depict the trends.

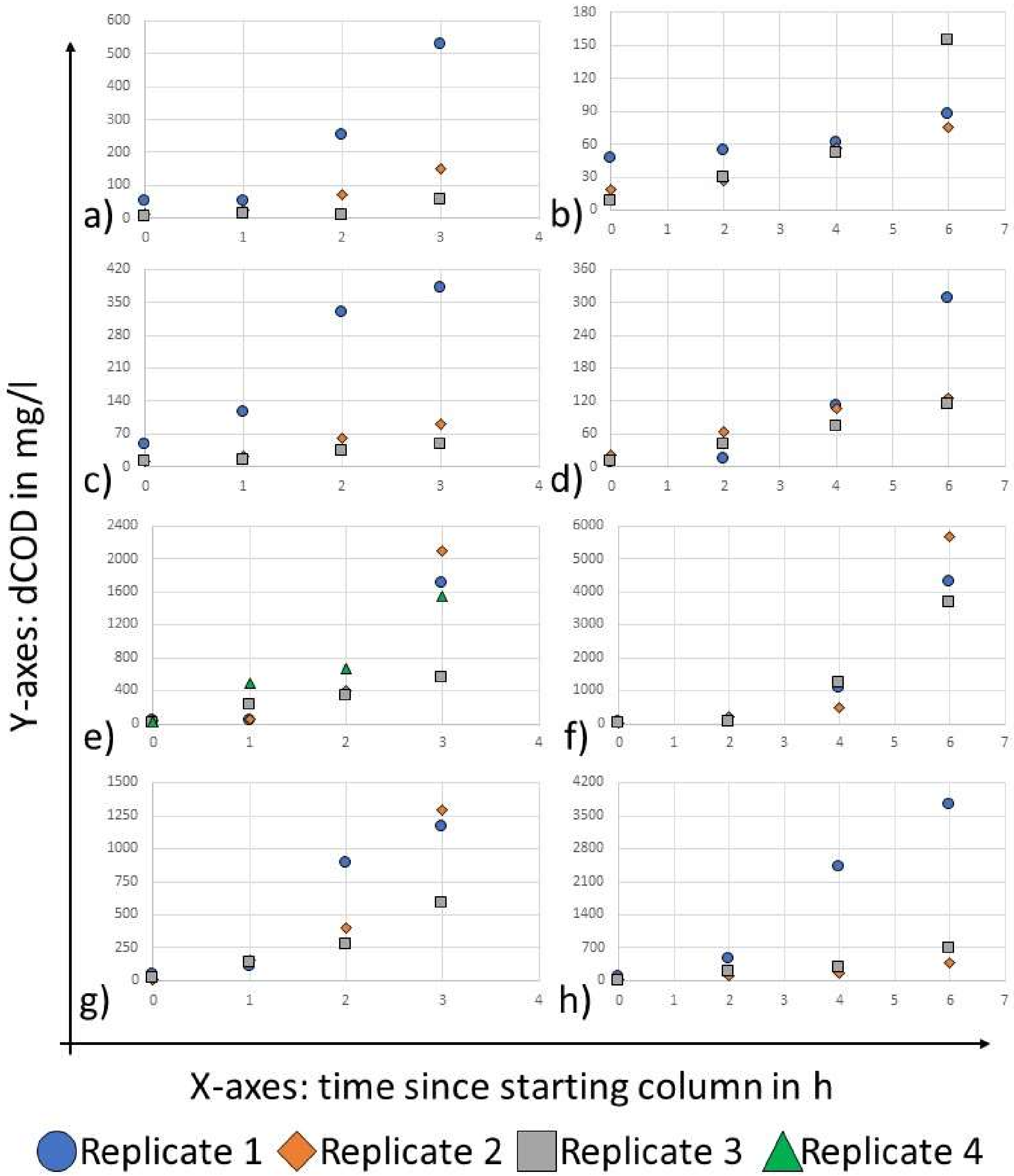


Figure 4-12: dCOD measurements for conical tank tests. a) +++, b) ++-, c) +-+, d) +--, e) -++, f) -+-, g) --+, h) ---. Note the varying scales on the y-axes, made necessary to depict the trends.

The statistical analysis yielded the following results:

Levene's Test of Equality of Error Variances based on the median showed that the assumption of equal variances was not violated for any of the three dependent variables (Table 4-3), allowing for the ANOVA to be conducted.

Table 4-3: Results of Levene's Test of Equality of Error Variances based on the median.

	Levene Statistic	df1	df2	Sig.
TS	.644	7	17	.714
COD	.835	7	17	.573
dCOD	.741	7	17	.641

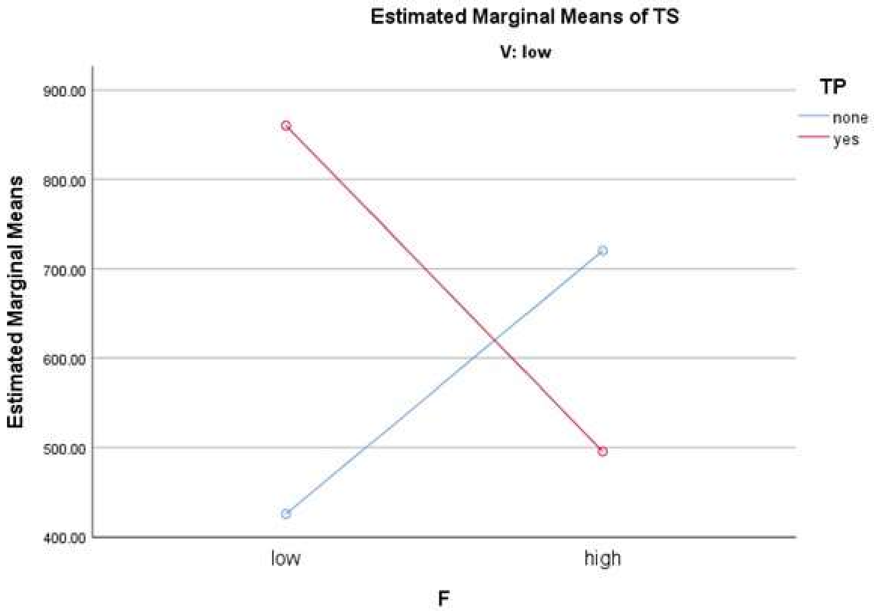
Significant **ANOVA results** are shown in Table 4-4. Only those effects of factors and interactions on independent variables are shown that displayed a high statistical significance ($p \leq 0.05$). These results indicate that TS are dependent on V, an interaction of TP and F, and a three-way interaction between V, TP, and F. COD appears to be dependent only on V, whereas dCOD appears dependent on V, TP, and the interaction of both. However, the two-way interaction of TP and F could, in turn, be moderated by V.

Table 4-4: Tests of Between-Subject Effects of the Three-Way ANOVA.

	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	p	Partial Eta Squared	Noncent. Parameter
V	TS	1679966.401	1	1679966.401	54.228	0.000	0.761	54.228
	COD	1913974.459	1	1913974.459	24.642	0.000	0.592	24.642
	dCOD	1009187.501	1	1009187.501	40.125	0.000	0.702	40.125
TP	dCOD	128834.797	1	128834.797	5.122	0.037	0.232	5.122
V * TP	dCOD	124304.731	1	124304.731	4.942	0.040	0.225	4.942
TP * F	TS	157852.444	1	157852.444	5.095	0.037	0.231	5.095
V * TP * F	TS	179141.424	1	179141.424	5.783	0.028	0.254	5.783

Error	TS	526654.063	17	30979.651
	COD	1320392.946	17	77670.173
	dCOD	427568.483	17	25151.087

Splitting the dataset into those values with V = + and those values with V = -, and a subsequent Two-Way ANOVA for the interaction of TP with F reveals that this interaction is moderated by the third factor V. While there is a significant effect for the interaction of TP * F at low V ($p = 0.034$), there is none at high V ($p = 0.755$). The plots for the estimated marginal means illustrate this clearly (Figure 4-13). Therefore, the effect of this two-way interaction is not considered to be significant.



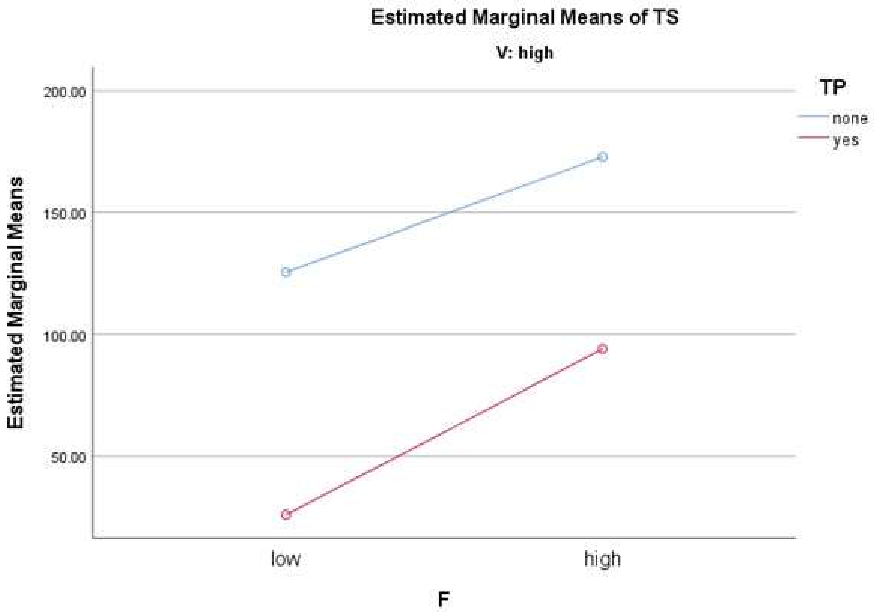


Figure 4-13: Plots of estimated marginal means of TS for the interaction of TP and F, and low and high levels for V, respectively. While the plot lines cross for low V, indicating an interaction, they do not cross for high V.

When reviewing the estimated marginal means for the effects shown in Table 4-4, it is revealed that the 95% confidence intervals for the high and low settings of the effects overlap in most cases (Table 4-5), indicating that one cannot distinguish clearly between the levels of TP, the two-way interactions of V*TP and TP*F, and the three-way interaction of V*TP*F. The effect of these factors and interactions is therefore not considered to be significant. The intervals are distinct from each other only for the different levels of V, which is consequently left as the remaining significant factor affecting TS, COD, and dCOD in the overflowing liquid.

Table 4-5: 95% Confidence Intervals for the estimated marginal means of the dependent variables at the different levels of the significant effects. In most cases, the intervals overlap.

			95% Confidence Interval		
Effect	Dep. Variable	Level	Lower Bound	Upper Bound	Overlap
V	TS	-	521.579	729.169	No
		+	-2.637	211.762	
V	COD	-	531.020	859.718	No
		+	-30.272	309.205	
V	dCOD	-	352.325	539.371	No
		+	-54.403	138.778	
TP	dCOD	-	75.314	268.494	Yes
		+	222.608	409.654	
V * TP	dCOD	- * -	166.301	439.499	Yes
		- * +	461.019	716.572	
		+ * -	-95.691	177.507	
		+ * +	-93.132	180.066	
TP * F	TS	- * -	123.922	427.128	Yes
		- * +	294.924	598.129	
		+ * -	291.452	594.658	
		+ * +	152.955	436.577	

Effect	Dep. Variable	Level	95% Confidence Interval Lower Bound	Upper Bound	Overlap
V * TP * F	TS	- * - * -	211.081	639.879	Yes
		- * - * +	505.918	934.715	
		- * + * -	645.748	1074.545	
		- * + * +	309.878	681.227	
		+ * - * -	-88.828	339.969	
		+ * - * +	-41.662	387.135	
		+ * + * -	-188.435	240.362	
		+ * + * +	-120.419	308.378	

4.5 Discussion

Both in the settling columns with real faeces and in the conical tank with synthetic faeces, settling did not occur completely. This corresponds to our observations during field tests and confirms the need for additional processes to achieve solid-liquid separation. Toilet paper seems to be the crucial component preventing the settling of solids. And while toilet paper is not used everywhere in the world, with some people using other types of paper, and many using water, it can be expected that a significant portion of NMT users may, at some point, use toilet paper and input it into the NMT. Therefore, its effects on settling should not be ignored. With its low dry density of 260 g/l (Durukan and Karadagli, 2019), toilet paper should float. However, once soaked with water, it appears to remain at a static water level in the column and create a matrix sufficiently strong to keep faeces in suspension. Potentially, gases exiting the faeces (Levitt and Duane, 1972) were trapped under toilet paper, creating the visible “ballooning” effect. Theoretically, toilet paper is designed to disintegrate easily through water movement in the sewers, even though this does not always happen sufficiently well (Eren and Karadagli, 2012; Elmas and Ozturk, 2019). Field tests of a different onsite sanitation system encountered a similar problem with toilet paper: A conveyor belt system designed to separate solids from liquids as form of pre-treatment repeatedly jammed and even broke because of not disintegrated toilet paper (Sahondo *et al.*, 2019). In our experiments, no stirring was carried out that could have caused toilet paper disintegration, as currently, the NMT's collection tank operates without stirring. However, ongoing research into maceration of faeces might prove that it is advantageous for auger-transport and dewatering, which could solve the problem of intact toilet paper. The experience of Sahondo *et al.* (2019), however, could also indicate that when used, toilet paper may cause complications for maceration within the NMT.

The observations in both sets of experiments were distinctly different from settling processes in municipal wastewater or faecal sludge treatment: Toilet paper and faeces were still intact and did not settle well. The conical tank appeared to promote better settling than the vertical columns, which corresponds to the use of this shape in municipal treatment (Dodane and Bassan, 2014; Metcalf & Eddy Inc. *et al.*, 2014). However, this observation will have to be validated using real faeces. While settling in septic tanks does not frequently appear to be a subject of research, the breakdown of toilet paper seems to be a consideration for their users nonetheless, as can be deduced from the existence of *septic tank safe toilet tissue* (Freedom Living, 2020).

Displacement was shown to promote solid-liquid separation: By lowering the liquid overflow level, a smaller maximum liquid volume was created, thus lowering the ratio of liquids to solids in the tank, which is tantamount to achieving better phase separation. However, a too high solids content in the cylindrical settling columns caused the creation of a plug, under which further liquids were trapped. While the use of a conical tank in the NMT is likely to reduce the risk of plugs forming, there is still a chance for 'bridging' to occur, a type of clogging observed for example in grain silos (Wu *et al.*, 2009). This could be exacerbated by the high stickiness of faeces, and their tendency to adhere to even smooth surfaces (Wang *et al.*, 2019). Therefore, it may be worth investigating whether a higher liquid content would reduce the risk of bridging. As can be seen in water flush toilets, liquid is a good medium to greatly reduce the adhesion of faeces to smooth surfaces. Therefore, some liquid might have to remain in the tank. Future research could investigate bridging of real faeces in the NMT collection tank, and whether liquid content affects the occurrence of bridging.

It seems unsurprising that measured COD concentrations rose steadily across all samples in both sets of experiments, save for some potential outliers. The longer faeces and urine remain mixed, the more organic compounds could dissolve into the liquid phase. This has implications for the operation of the collection tank in the NMT: To reduce the organic burden on the downstream membrane treatment processes (Kamranvand *et al.*, 2018), it appears desirable to reduce contact time between faeces and urine, either by removing faeces from the tank as quickly as possible, or by lowering the liquid outflow point as much as possible, effectively draining the liquid quicker. Removing the faeces quickly would require more frequent operation of the auger, which requires energy. As the NMT is designed to be energy self-sufficient, higher energy consumption is undesirable. A lower outflow, and consequently lower liquid content in the collection tank would not require additional energy but might result in bridging. Hence, where on the spectrum between the two modes of operation – frequent emptying or low liquid overflow – the optimum will lie depends on the requirements for the auger to perform, whether a macerator is added to the tank, and whether bridging is likely to occur with real faeces. Current thinking on next steps in NMT design does indeed include a macerating blade on the auger to encourage solids pick-up by the screw and reduce the risks of blockages caused by paper and undigested solids (Ravndal *et al.*, 2019). Ongoing NMT research will yield insights into these questions which have been informed by the presented settlement and displacement experiments.

The statistical analysis of the second dataset yielded the conclusion that, other than time, only the effective tank size had a significant effect on the quality of the overflowing liquid. This conclusion seems plausible: As suspected, the higher liquid volume appears to dilute the concentration of solid particles and organic load. Thus, the larger the liquid volume, the lower the pollution effect from a given amount of faeces would be. This would indicate that operating the tank with a high liquid volume and frequent solids removal might be favourable.

Considering that it did not seem to make a significant difference to the liquid overflow quality whether toilet paper was used or not, but the use of toilet paper does appear to cause suspension of solids that would otherwise settle, it seems advisable to avoid the use of toilet paper in the NMT. However, this would either add a burden to the solid waste collected in the toilet room, or require a significant behaviour change for a large number of potential users, who habitually wipe rather than wash. Anal cleansing through washing would also add more liquid to the toilet, which would then need to be treated. Maceration of the tank's contents could facilitate settling, but would likely result in higher TS and COD concentrations in the liquid phase. Advising the use of toilet paper that disintegrates especially easily, like *septic tank safe toilet tissue*, may be another approach to promote settling in the NMT's collection tank.

4.6 Conclusions

The presented research confirmed the casual observation of previous testing that settling of faeces and toilet paper in urine does not occur to a satisfactory degree in containers of similar volume and geometry to that of the NMT's collection tank. Toilet paper could be identified as instrumental inhibitor to settling and thus to effective solid-liquid separation.

A lower liquid overflow level could be shown to result in better solid-liquid separation in the tank. However, the study also concluded that contact time and liquid volume were affecting the quality of the overflowing liquid, and a higher liquid volume in the tank resulted in better quality overflowing liquid. These contradicting results could not be reconciled definitively.

In fact, it is practically impossible to decide how to best operate the NMT's collection tank without considering the entire NMT holistically. The NMT is a complex product consisting of multiple sub-products, or sub-systems, that affect and interact with one another. Before the subsystems can be integrated into a complete system to test all interactions in a fully functioning physical prototype, it is sensible to test the sub-systems individually and understand how they operate depending on various inputs. The present study has been such a sub-system test and only provides some information on which the decision of tank operation will be based. It is one of many prototype experiments required to develop a product as complex as the NMT.

4.7 Acknowledgements

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5 Using expert interviews to validate and generalise a visual tool for the planning and communication of prototype tests in product development

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5.1 Abstract

The testing of prototypes is a vital part of product development projects. In this study, a previously developed visual test planning tool, designed to facilitate communication and planning of prototype tests, is validated and improved using the combined knowledge of ten experts in prototyping and product development. In semi-structured interviews, the experts are questioned about important aspects and problems when testing prototypes, and their opinion of the visual tool. A combined deductive-inductive analysis of the interview transcripts yielded three super-categories of responses. Communication and planning are validated to be the most important, yet also most problematic aspects of planning and executing prototype tests. All interviewees believe that a visual tool could find use in prototype testing. A set of recommendations for generalising and improving the tool is developed from the experts' responses, and a modular, generally applicable version is presented.

Keywords: Prototyping, interdisciplinary communication, testing

Abbreviations: ALT – Accelerated Life Testing; DOE – Design of Experiments; DUR – Durability Testing; HALT – Highly Accelerated Life Testing; HnS – Health and Safety; Int. Std. – International Standard; PD – Product Development; Rel. – Reliability Testing; UCD – User Centred Design

5.2 Introduction

Prototyping, the process of designing, building, and testing prototypes, is well-recognised as important part of product development (PD) (Schork and Kirchner, 2018). Ulrich and Eppinger (2016) identify *learning, communication, integration*, and *milestones* as the four major purposes of prototypes. Learning, which we define for this purpose as 'collecting and analysing information about the product in development' can be achieved by testing of prototypes, an aspect of PD that still remains under-explored in academic literature (Tahera, Eckert and Earl, 2015). Camburn et al. (2017) explain how unique prototyping strategies determine what one can learn from a prototype and discuss multiple aspects to be considered for the development of prototypes. However, they do not consider the planning of prototype tests for the development of a prototyping strategy.

In a previous study (Hennigs, Parker, *et al.*, 2019a) we developed a visual test planning tool (Figure 5-1) based on existing academic literature about PD, prototyping, testing, and experimentation. This tool was aimed at facilitating communication and planning of prototype tests for the Nano Membrane Toilet, a novel non-sewered dry sanitation technology. If found useful, the tool could be generalised to be applied in other PD projects. However, validating the usefulness of the tool or generalising it in an empirical way would require multiple case studies with projects of different sizes and backgrounds, an endeavour beyond our means.

Instead, a qualitative approach could draw from expert knowledge, condensing the experience of numerous PD projects into a small number of interviews. In studying what experts in the field of prototyping and PD consider important aspects of and barriers to testing prototypes, and if they think a visual tool could address these important aspects and barriers, the usefulness of the tool could be validated and improved. Furthermore, questioning a broad spectrum of experts about their opinion of the visual testing tool and how it could be generalised and improved would likely yield a set of recommendations that would achieve this generalisation and improvement.

This paper aims to collect and analyse knowledge about the important aspects of and barriers to effective prototype testing, validate the usefulness of a visual tool for prototype testing in PD, and to develop a generally applicable, improved version of the testing tool developed in our previous study.

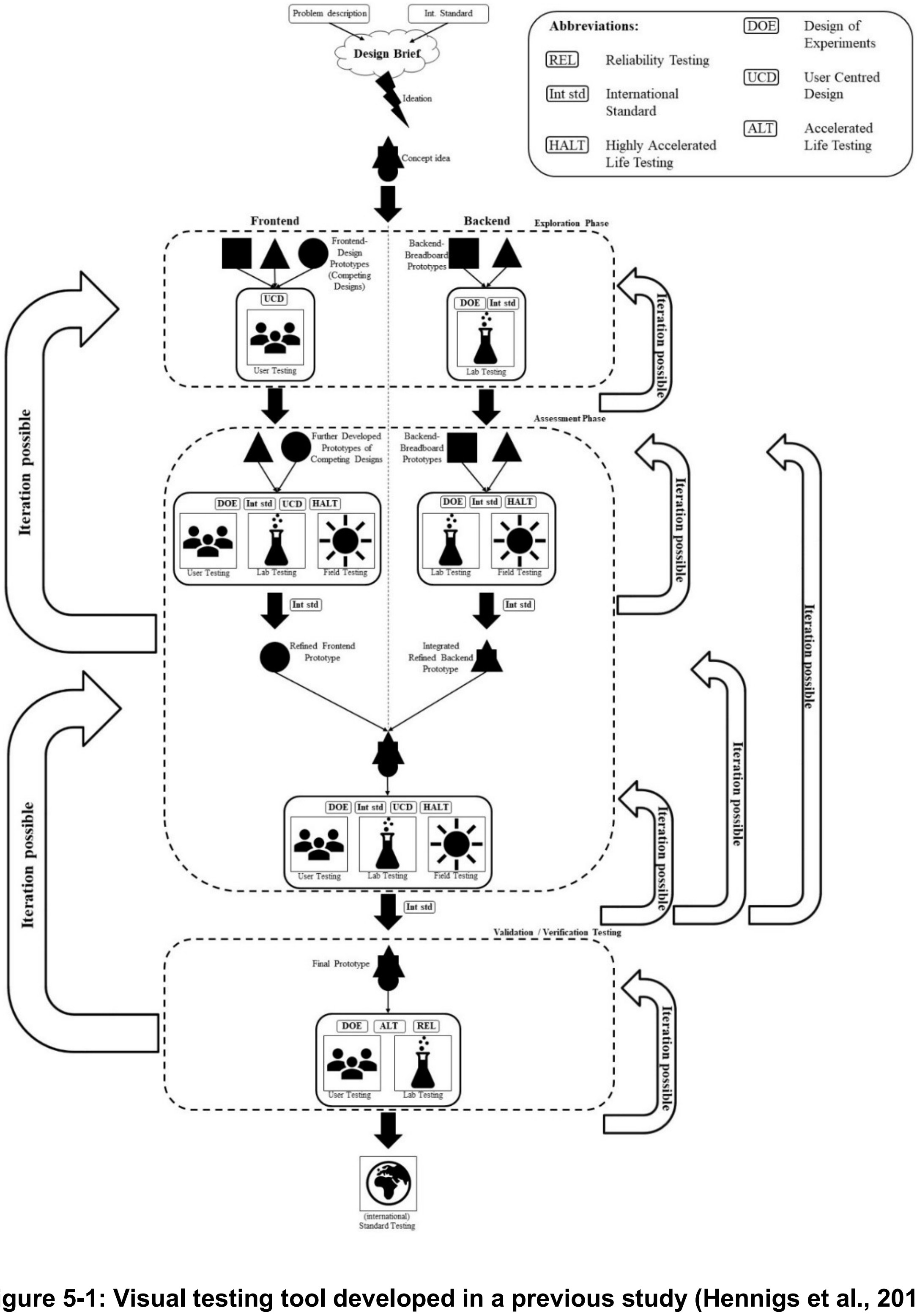

Figure 5-1: Visual testing tool developed in a previous study (Hennigs et al., 2019, Version 1).

5.3 Methodology

The qualitative approach of this study was to conduct expert interviews (Bogner, Littig and Menz, 2009). Thus, in a first step, suitable experts were identified and contacted, as described in section 5.3.1. The following sections describe the format of the interviews (section 5.3.2) and their analysis (section 5.3.3).

5.3.1 Sampling

To find expert interviewees, i.e. people with sufficient experience in and knowledge about product development and testing of prototypes, the professional networking service LinkedIn was searched for users with an appropriate profile, who were then contacted on the website. Similarly, personal and professional networks were queried via email or personal conversation. To supplement this approach, companies specialising in particular types of products were researched online and contacted via email or the company’s website. Over the course of several months, interviews with ten individuals were conducted. While more unique items of experience may likely have been gathered from further participants, a general saturation (Strauss and Corbin, 1998; Bryman and Bell, 2015) regarding the main conclusions was achieved after the ten interviews (Table 5-1).

5.3.2 Interviews

After agreeing to participate, the experts were sent study information sheets and a copy of the original version of the visual test planning tool, to improve their understanding of the study aims. The participants were interviewed in a semi-structured format, using a set of broad questions that were used to guide the conversation, which was also allowed to divert from the questions. In most cases, additional follow-up questions were asked when appropriate and necessary.

The guiding questions were:

1. In your opinion, what are the three most important aspects of testing prototypes in product development processes?
2. In your experience, what are the most common problems that product developers encounter when planning prototyping / prototype-testing?

3. Do you think different approaches to testing, or types of tests are seen as separate activities in the product development process?
4. (After being presented the visual testing tool) What do you think about the flow chart?
5. Do you think this flow-chart could find practical application in a product development process?
6. Do you think you could find it useful for your work in particular?
7. How would you improve the flow chart to make it more useful for your work?

Except for one interview, which was conducted in person and recorded using a smartphone, all interviews were held and recorded using Skype. The recorded files, containing video and audio information, were converted into pure audio files of mp3 format and transcribed and analysed using NVivo software.

5.3.3 Interview Analysis

The analysis followed a combined deductive-inductive approach, as modification of Braun and Clarke's (2006) description of thematic analysis. Rather than starting the coding process without any pre-conceived themes, the interviews were analysed for a specific purpose, and the inductive development of codes and sub-categories common for thematic analysis occurred only after an initial, deductive round of coding.

As a first step of familiarisation with the data, all interviews were transcribed verbatim, with the exclusion of personal identifiers and commercially sensitive information, which were replaced with anonymised words in brackets. From the interviews and publicly available information, the interviewee profiles in Table 5-1 were created. Before beginning the analysis, all transcripts were then read again multiple times.

In the next deductive step, based on the questions used in the semi-structured interviews, eight questions were created, for which the transcripts were then thoroughly queried. Potential answers to these questions were then coded. The questions were also used as titles of the original categories into which the developed codes would be sorted, with the last category being a pool for unanticipated codes and potential other categories. The eight original categories were:

a. What are important aspects of planning prototype tests?
b. What are big problems when planning prototype tests?
c. Are testing activities done separately or is testing one domain?
d. How do the experts view the visual tool?
e. What do they like about it?
f. What don't they like about it?
g. Do they think it's useful to have a visual tool?
h. Are there any other observations or comments that apply to the research but do not fit into the above categories?

The initial round of coding was followed by an inductive step: the codes were arranged and combined into sub-categories, which were then used to lead a second round of coding. Afterwards, a multi-stage review sorted and combined all categories and sub-categories into three super-categories, designed to compile the information extracted from the transcripts into distinct but interlinked aspects of the experts' responses. The three super-categories were

A. Important aspects of planning prototype tests
B. How a visual tool could add value to planning prototype tests
C. How the tool could be improved

Table 5-1: Interviewee profiles. Interview time ranged from 28 to 74 minutes, with an average of 46.6 minutes. In the analysis, interviewees are quoted using their randomly assigned cyphers, to prevent association.

Interview	Job description	Experience in prototype testing	Years of expertise	Interview duration
1	IT project manager at globally active NGO	Has managed multiple software development projects, currently overseeing implementation and testing of a large-scale software move	>5	50 mins

Interview	Job description	Experience in prototype testing	Years of expertise	Interview duration
2	Innovation and strategy consultant for global innovation consultancy	Is a trained veterinary surgeon and biomedical engineer, ran several small businesses before current role as consultant	>9	33 mins
3	Senior lecturer at European University	Has been researching testing in engineering product development since PhD	>10	51 mins
4	Project Manager / Lead engineer at private company	Has been leading the development of a novel technology from its inception, including testing of numerous prototypes	>5	30 mins
5	Design Engineer at company developing bespoke medical devices	Has experience with developing and testing numerous prototypes since PhD	>6	54 mins
6	Senior Lecturer in Design at European university	Has experience in computer aided product development, has set up a design and product development company and brought several products to market	>20	40 mins
7	Research Assistant at European University	Has experience in materials selection, product development, and testing. Previously tested prototypes during postdoc and has worked as PD scientist for large international company.	>12	28 mins

Interview	Job description	Experience in prototype testing	Years of expertise	Interview duration
8	Chief Scientific Officer of small innovative company developing wearable technology	Has developed a novel technology from conception to market, and is currently leading the prototype testing for next generation of products	>6	69 mins
9	Chief Technology Officer for software start-up	Has developed multiple web applications for design agency and has since co-founded a start-up developing a citywide mobility platform	>6	37 mins
10	Director of company for electronic product design and development	Is a design and prototype specialist, expert in a range of disciplines including electronic product design, electronic product production and has brought many products to market	>30	74 mins

5.3.4 Redevelopment of the visual test planning tool

Super category C. comprised the experts' recommendations for changing the existing visual test planning tool (Figure 5-1) to improve its utility and its general applicability. The main recommendations were considered and implemented into a new version of the tool. As per the suggestions of several experts, the tool's visual elements were divided into modules (modularisation), and the option of drawing the modules on multiples layers was introduced (layering), thus enhancing the tool's customisability and utility for communication, respectively.

Testing the new tool by recording first-time users' response

The new version of the tool was tested in a focus group approach (Seal, Bogart and Ehrhardt, 1998; Webb, 2002; Rosenthal, 2016): At an international conference for water and development, it was presented in a workshop, in which

15 participants practised its use in a group exercise. In three groups of five people, the attendees used the tool and basic stationery to develop visual testing strategies for fictitious water-related case studies of PD projects (Table 5-2). The case studies were kept simple, but all contained information about the time pressures, budget constraints, whether front end, back end, or both are being developed, and whether the project involved developing software, hardware, or both. After 45 minutes, the groups presented their results and discussed their experience of using the tool.

Four researchers observed the group exercise and subsequent discussion. Afterwards, they recorded their observation in field notes. These were then analysed to assess whether the tool could be intuitively applied by first-time users, and whether the participants encountered any problems during the exercise.

Table 5-2: Case studies of simple water-related PD projects to be used in workshop.

	Case Study 1	Case Study 2	Case Study 3
Text of case study supplied to participants	An internationally active foundation, funded by philanthropic billionaires, want to develop a waterless non-sewered sanitation technology that safely treats human waste and recovers nutrients and energy, should be available in 5 years.	An outbreak of gastro-intestinal infections in an informal settlement of a large sub-Saharan African City has prompted the city council to contract a local company to develop handwashing stations. The council will provide connections to running water and sewage / wastewater disposal; the focus is on developing an easy to use, hygienic handwashing station that only uses little water. It should be cheap and available as quickly as possible.	A private water utility company wants to develop a smart water meter that connects to smartphones, alerts users of increased water usage, and allows real time cost calculation. Ample funds have been allocated for the product to be available within one year.
Time pressure	Low to medium	High	Medium to high
Budget constraints	practically none	medium to high	none
Hardware – software	mainly hardware	only hardware development	both
Back end – front end	both	only front end	both

5.3.5 Ethics Statement

The methodologies used for this study were approved by the Cranfield University Research Ethics Committee (Approval reference CURES/7912/2019 for the interviews, and CURES/9407/2019 for the workshop). Written, informed consent was obtained from all participants, whereby the supplied information sheets emphasized the voluntary nature of participation and the option to leave the study at any time or opt out of answering any questions.

5.4 Results

The coded responses of the interviewed experts are described in the three following sections. The complete codebook can be found in the Appendix (Section 5.9).

5.4.1 Category A. Important aspects of planning prototype tests

This theme subsumes the codes from the originally applied themes a, b, and c, as well as aspects initially coded under theme h. It comprises nine aspects that found mention in multiple interviews, and from various perspectives.

Communication (Aggregated from 9 interviews)

Communication was mentioned as a crucial aspect of successful prototype testing and product development in general. In the experience of all interviewees, prototype testing is an exercise that involve multiple actors. This can range from a small start-up-level company of five to ten people developing an app to a multinational corporation with discrete departments for finance, testing, design, etc., and it will often involve cooperation with external companies, as partners, customers or contractors. Communicating effectively with all of these stakeholders can be challenging but is vital for the success of the project. Three experts, for example, emphasised how important it is to get feedback about the product from users and customers, early and often. This can take the form of informal chats or more organised user tests and ensures that what is being developed aligns with the customer's wishes, or with the users' needs. One interviewee explains about the importance of frequent communication with their customer: "*[…] and then we'd slowly build it up and have their constant feedback and constant check in, so that we made sure that what we were building was right, because one thing that can go really wrong in technology projects is that you have a conversation, with a business, and you gain an understanding of what their needs are, and you build the solution based on that understanding, and if* *your understanding is flawed, it's not gonna be until you show them what you've built that they recognise that*." (Interviewee 1986)

Even though communication has such a high value for prototype testing, or rather because of its importance, it is also recognised as a significant problem: eight of the experts talked about the problems causing and resulting from poor communication. A persisting sentiment was that it is difficult to communicate between stakeholders with different backgrounds, as they do not share the same understanding of the process. Amongst others, this can be the case between software and hardware developers, between product developers and their customers, between small, less organised start-ups and larger companies with long-established procedures, between the finance and testing departments of the same company, or between an industrial design company and an electronics developer. Interviewee 5555 remembers: "*[…] so I had the external companies that […] asked me to do the testing. It was quite difficult to communicate, sometimes, the type of work that you'd done, because the outcome of types of tests that we'd conducted wasn't necessarily directly transferrable into something they understood.*"

Recurring problems were that testing was under-appreciated, and the time and resources required for effective testing were underestimated, and that managing expectations was a challenging communication effort. Problems caused by poor communication were delays, financial loss, and frustration, because products were not developed in the expected timeframe or budget, or because they did not fulfil the customer's expectations.

Strategic planning of tests (Aggregated from 9 interviews)

An aspect that was similarly perceived as important by 9 of the interviewed experts was the thorough and strategic planning of prototype tests. One interviewee remembered that, in their experience, early exploratory testing would often not be planned out, but for more mature prototypes, planning would become increasingly important. However, the more prominent opinion was, that planning has value from the earliest stages of a PD project. For instance, a clear strategy could be used for communication purposes, in order to gather stakeholder support and agreement: "*So I find having a testing strategy that everyone understands and buys into is really important, because it enables people to appreciate the value of testing, but also appreciate the work and effort involved.*" (Interviewee 1986)

Another benefit of thorough planning mentioned by the participants was maximising the knowledge gathered through testing. For this aim, it is crucial to define clear test questions and clear failure criteria when planning the tests. Developing the prototype with the tests in mind ensures that the tests can be carried out as intended, and user tests should be carried out with real users "*who are naïve to the technology*" (Interviewee 2063). Resource considerations affect test planning in multiple ways. For example, the available time and budget will determine how elaborate tests can be or how many iterations the prototype can undergo. Understanding the scope of the tests can thus be an essential part of generating a focused testing strategy.

Especially for novel technologies, it can be difficult to identify the right testing approaches and protocols: *"[…] a thing like this hadn't existed before, so how do you even test it?*" (Interviewee 5920). To develop the appropriate tests, it can be useful to establish how similar technologies are tested and to adapt these procedures. One interviewee explained that for them, validating the test procedures may take up more time than carrying out the tests, and that the know-how of testing a specific technology is itself valuable intellectual property which can drive innovation processes:

"*Actually you could go as far as to say a big part of what is enabling a lot of improvements in our second generation technology *is* the improved testing protocols […] and I very often try to remind myself and everyone around me to keep us sane that these protocols that we're developing are part of our, like, intellectual property. They're part of our thought leadership in knowing how to test these systems and then quantify outcomes and then optimise systems for those outcomes […]. 'Cause these tools we're building, or have built, and will continue to improve are a really important part of our journey to develop new technology* […]." (Interviewee 5920)

As with communication, the importance of planning implies that it can be problematic. Half of the interviewees mentioned having encountered difficulties with planning testing of prototypes. For example, it can be challenging to decide which tests are necessary, what the important measurands are, and to not lose sight of the bigger picture. This uncertainty is a recurring issue for several experts, and developing a new product often requires a healthy degree of flexibility, as described in the following section. This means, however, that one cannot plan for unexpected test results, which in turn may yield new questions that may have to be answered with unplanned tests, which then may have to be developed ad hoc. Thus, a good testing strategy will have to anticipate testing outcomes as well as possible, but must also allow for flexibility and iteration.

Iteration and flexibility (Aggregated from 8 interviews)

Another aspect that most experts mentioned is the importance of iteration. As interviewee 3577 phrased it, "*I'd be very surprised if you solved all the problems straight away. I just- I very much doubt that every really happens*." Iteration is seen as a necessary aspect of any prototyping activity, and even a thoroughly planned and executed PD process is expected to yield some test results that require minor adjustments to the design. Particularly for the early exploratory stage of PD, building many cheap, low-fidelity prototypes is viewed by the experts as a beneficial exercise to learn about design ideas.

With this need for iteration comes the acknowledgement that flexibility is a vital quality of a testing team. As requirements may change, so can the focus of testing. New measurands might be important, or a completely different prototype may need to be developed.

On the other hand, iterating can be costly, and increasingly so as the product maturity increases. Thus, budget constraints may restrict the number of iterations that can be undertaken. Similarly, time constraints may not allow for a long iteration loop. One interviewee quotes a colleague:

"*Decision making processes [are] like paddling a canoe down a river. You keep going, you come to a fork, you pick one direction, and you paddle down that fork.*

And then you get to another one, and you make another branch off, and it's really, really difficult if you decide you've gone the wrong way, to turn around and paddle back upstream. So, you tend to only go back to the last decision point and reiterate from there. Even though it's not ideal it's what tends to happen in reality." (Interviewee 5555)

Another interviewee explains that, if developing a physical prototype is very expensive, which is the case for electronic products, they might only iterate once in the entire PD process, or often not at all. This alternative approach of only going through one very long iteration loop, rather than multiple small ones as described by Interviewee 5555, is designed to limit cost and time.

Timing (Aggregated from 7 interviews)

Both planning and iteration affect, and are affected by the time management of a PD project. Four experts talked about how difficult it is to have the necessary resources available at the time for which the tests are planned. Testing rigs often have to be booked in advance, so the prototype needs to be test-ready for when the rig is booked. Similarly, in the case of software development, user tests may require certain staff of the customer's company, whose workload may not allow for testing the new software when required.

Coordinating tests before decision points can be a challenge: "*So often you would get the results of some testing and you'd have to wait for the results of something else for it to combine together, to be able to make a next-step decision.*" (Interviewee 5555) In other cases, the deadline for releasing a new product-version may limit what upgrades can be tested thoroughly enough to be included in the new version. As described above, testing is often under-appreciated, which may cause senior management or customers to demand shorter testing times: "*[…] so they'll squeeze the testing timelines and put a lot of pressure to try and make sure you would have the same quality of testing in two months as you would have had in six months […]*" (Interviewee 1986).

Small companies at a start-up level tend to spend a lot of time on testing in research and development. Such tests can often be of an exploratory nature, and it can be extremely difficult to accurately predict the timelines for these exercises.

Learning from testing (Aggregated from 6 interviews)

Learning and knowledge generation appear to be the most prevalent aims of prototype testing, according to six experts. Four of them described finding faults with a prototype, or the prototype failing a test, as a positive outcome. One recurring sentiment appears to be that it is better to find and correct problems during a product's development rather than after its release to market. Additionally, a product that passes every test may not have been tested correctly, and "*a negative output, if actually analysed properly, can actually spin out even greater solutions at the end*" (Interviewee 3847)

Two respondents both talked about the importance of thoroughly analysing the test results, not only towards the information that was gained about the prototype, but also towards the test procedure itself. The analysis of the test procedure can be a valuable resource in designing future tests.

Lastly, three experts mentioned the importance of considering both quantitative and qualitative test results to learn about a product. While a lot of technical information about a product may only be gathered in rigorous quantitative tests, there is also a lot of information to be gathered by qualitative tests.

Documenting of testing results and progress (Aggregated from 6 interviews)

For the aim of effectively analysing tests and test results, but also for communication and reporting purposes, documentation is viewed as a critical aspect of prototype testing. Examples of documentation types varied from notes to digital spreadsheets to photographs with accompanying notes. One expert did also discuss the problem of deciding which data to record, "*without getting bogged down in information*" (Interviewee 3375).

Testing throughout PD – one domain or many (Aggregated from 5 interviews)

When prompted the question whether or not the various tests throughout a PD project are seen as a single domain, five interviewees explained that tests are seen as separate domains in certain cases. In software development, front end tests would generally be performed by other people than those carrying out back end tests. In the case of a software product being implemented for the daily business of a large organisation, tests were categorised according to priority, into technical, financial, and user experience tests. For three respondents, it depended on the product's maturity: "*It depends where you are in the process. At the beginning, when, where your prototypes, er, look nothing like the finished product, erm, and you're testing individual elements, they're very much different processes. At the end, when you have a product in your hand that looks more similar, or is used in a similar way, erm, then I think they, they become very tightly linked processes.*" (Interviewee 2063)

In some cases, tests have to be combined despite the more complicated test design. This can be the case if the functionality of a technology needs human user input to be tested, thus requiring a combination of user testing and functionality testing.

Risk Reduction (Aggregated from 4 interviews)

While only discussed by four of the ten interviewees, the subject of risk reduction was still considered an important aspect of testing prototypes. There are two major ways in which risk considerations are seen as part of prototype testing. Firstly, risk reduction is an important outcome of prototype testing, as tests yield information about the product in development. Secondly, the severity of a certain type of risk would determine the importance of a test, as well as the importance of a problem discovered in a test. For example, in software testing, a minor bug would be recorded, but might not be addressed until much later, whereas a major functionality issue would be attended to immediately. Similarly, if the biggest risk of a PD project is consumer adoption, user tests would be a priority, whereas testing the correct functionality would be prioritised over user friendliness for a fee calculator affecting the cash flow of a company.

A particular issue that was addressed by two respondents was the problem of having to invest considerable amounts of time and resources into a project, before a testable prototype could be developed that addresses the greatest risk to the PD project, for example the energy consumption of a new electronic device: "*So one of the biggest problems that we have, especially with handheld products nowadays, is the question over battery life. So the issue that you have is until you have the hardware in front of you, and the hardware is running Version 1 software, you cannot possibly know how long the batteries may last.*" (Interviewee 8294) As the most important tests are those addressing the greatest risk, developing the right prototype to carry out those tests is prioritised.

Hardware-Software dichotomy (Aggregated from 3 interviews)

Three respondents talked about software and how its development differs from developing hardware. "*Hardware: very expensive to make design changes, very long lead times, expensive, slow; software is everything hardware is not*" (Interviewee 5920). Unlike hardware, software is often released unfinished, and continues to be developed and updated after market-release. This is the case for 'pure' software products as well as the operating software of physical products. Software testing can be automated, but an important aspect of developing and testing software is its usability, which requires user testing.

5.4.2 Category B. How a visual tool could add value to planning prototype tests

This theme subsumes the codes from the originally applied themes e and g, as well as some aspects initially coded under theme d. A brief account of positive comments about the visual tool presented to the interviewees is followed by a description of how they thought a visual tool could facilitate processes in testing prototypes during product development.

Positive comments about the tool (Aggregated from 7 interviews)

Six of the experts mentioned that the PD process depicted in the tool looked similar to their understanding of PD processes, four liked the consideration of international standards in the test design of early stages of development, two complimented the use of multiple iteration arrows throughout the PD process, and the incorporation of multiple thought processes for a single stage of testing was positively remarked by one respondent, as was the dotted line separating back end and front end development, as it signifies that both are not developed independently from each other.

How a visual tool could be valuable (Aggregated from all 10 interviews)

All respondents thought a visual test planning tool could be beneficial in some way. Six of them thought such a tool could help communicate better. For example, four experts envisioned a visual tool to aid in stakeholder engagement. A visualisation of the PD process, and how testing of prototypes ties into it, would be an easy way to explain to customers, senior management, and others what the process will look like and how each stakeholder can support it. "*Anything that can turn […] and hour-long meeting into a visual aid that can be referred back to […] is really useful"* (Interviewee 1986). In facilitating communication, a tool could help set expectations for stakeholders, for example in terms of what resources they will need to allocate for testing at certain times. Further, three interviewees were confident that a visual tool could help raise an appreciation for testing with customers and management.

Four experts talked about how the tool could help plan tests better. For example, the visualisation could help people planning tests to keep the future PD process steps in mind, and develop tests accordingly, i.e. not lose sight of the bigger picture: "*But, looking at what the future of these prototypes is, is something that I'm not very good at myself, erm, and so having a visual that you can just got to […] if I'm in the exploration phase, being able to look forward and know 'Hey, I'm gonna need to be able to get to validation. Is the, the things that I'm exploring right now, are they even- do they even have a chance of making it?' […], I think is a good thing.*" (Interviewee 3375) Similarly, the visualisation could help the developers of front end tests consider back end processes, and vice versa. The same applies to the connections of software and hardware tests. A more modular version of the tool, as will be discussed below, was envisioned by one interviewee to be more of a toolbox, providing ideas to a testing planner from which to assemble their testing strategy.

In four interviews, mentions were found about how the tool could provide structure: "*I tend to work a bit more ad hoc, so having a bit, having something like this, which is easy to follow, that's not over-complicated, would be quite good for me.*" (Interviewee 3577) One interviewee mentioned that having a simple visual could be a valuable aid for maintaining an overview in the often-unstructured exploratory phase of PD, and another suggested that small to medium sized enterprises could benefit from such a tool as they develop a company structure. Two respondents mentioned that in their companies, a visualisation of their process structures could be used for training new staff.

5.4.3 Category C. How the tool could be improved

This theme subsumes the codes from the originally applied theme f, as well as some aspects initially coded under theme h. The experts' suggestions for amending or improving the visual tool were sorted into five categories, which are presented below.

Modularisation (Aggregated from 9 interviews)

Nine experts made suggestions that aimed at increasing the tool's flexibility. Four of them specifically talked about making it more adaptable to unique PD projects, for example interviewee 5555: "*I think, I like the flow chart. […] I think one thing to keep in the back of your mind is how it should be modified or adapted to different product types. Because there are some where it's a lot more critical to have the front end functionality, and maybe a slightly less functional back end […].*" A modular version of the tool could offer a variety of options that its user would combine to create a test planning flow chart for their unique application.

The most common request, made by six interviewees, was to change some of the terminology to fit a certain field of work. For example, software developers use different language than hardware developers, and developers of electronic products have other terminology than mechanical engineers: "*I don't know, maybe, yeah, I'd say some of the abbreviations […] and things like that we would tweak the language.*" (Interviewee 1986) An option to adjust the terminology used in the tool would allow professionals from various fields to use it. Similarly, two experts requested an option to change some of the symbols to better fit their applications.

Four respondents explained that the process depicted in the tool does not fully align with their processes. For example, in some cases a physical prototype would not be available until later stages of development, front end and back end integration would occur earlier or later in the project, or the two developments wouldn't align as well. Another comment made by two interviewees was about the consideration of other levels of testing, for example component, subsystem, and system levels. These would have to be visualised more accurately in some cases. An option to change the process elements and their positions would be required to adopt the tool more widely.

Other requests made by one interviewee each were the addition of a pilot-level testing phase, the consideration of durability testing and the consolidation of HALT, ALT, and reliability testing into one term, earlier front end-back end interaction, user testing for back end prototypes at earlier stages, and the use of physical prototypes in the ideation phase.

Additional Layers (Aggregated from 8 interviews)

In a similar line of thought, 8 respondents made mentions of adding additional elements to the flow chart, to enhance its utility for communication purposes. However, most of them recognised that this would increase its visual complexity and recommended that those layers could be presented either in parallel, or as individual visualisations:

"*You could have almost like a high-level and a low-level one. So, you could have a very basic one to explain within the management team to look what you're* *planning to do […], but actually when you go into testing, you can maybe have a load of […] pull outs.*" (Interviewee 3847) And similarly:

"*I'm kind of picturing it as being […] 'on the left page is this diagram, on the right page is a really nice graphic, or just a really nice simple explanation of each of those abbreviations and what's the benefits of using them […]*'" (Interviewee 3577)

Three experts mentioned that information flow is an important part of the testing of prototypes, and a visualisation of this would improve the usefulness of the tool. An example for this would be the type of documentation being used, and how the documented test results are reported and feed into decision making processes.

Other suggestions were a way to visualise the progress status of the project, e.g. by progress bar or with an option to add pictures of prototypes, additional information about the different visual elements of the flow chart, an way to display a specification matrix (mentioned by two respondents respectively), a visualisation of risks, cost considerations, what the focus of each phase is, or test outcomes (requested be one respondent each).

Iteration (Aggregated from 7 interviews)

While two respondents had liked the depiction of iteration arrows in the tool, seven others had suggestions of how iteration could be depicted more accurately for their understanding: three experts felt that there were too many iteration arrows depicted, and especially in later stages of PD, iteration should be much less likely to occur. Two others suggested to add an arrow that would lead from the bottom of the flow chart back to the top, feeding into the design concept development of a new version of the product. One respondent explained that in the case of electronics development, when prototyping is extremely expensive, there would often be only a single iteration, or no iteration at all. Another comment was that in some cases, an iteration loop would be interrupted, for example by changed specifications or, while building a prototype, the realisation that a design would not be feasible before even testing it. The interviewee suggested that in this case, branched arrows that did not complete a loop would be a useful visualisation.

Graphical presentation (Aggregated from 6 interviews)

Six respondents had comments on the graphical presentation of the tool. An issue mentioned by all of them was the lack of a comprehensive legend. All symbols and terms depicted in the tool should be found in a legend naming and, ideally, explaining them briefly. Two interviewees remarked that, at least at first glance, the tool looks too complex. One wished the tool were "*a little bit more […] graphically pleasing*" (Interviewee 3847), and suggested the process shape to be circular, rather than linear. Another suggestion was to add colour.

Highlighting useful advice (Aggregated from 4 interviews)

Four interviewees had suggestions of advice that could be beneficial for product developers and prototype testers, which could be added to the tool:

- Design and testing for manufacture should be considered from early on in the PD process
- Health and Safety considerations can be crucial for test planning, especially for user tests
- Searching for existing solutions within industry can be a fast and cheap alternative to designing and testing components and "*trying to reinvent the wheel*" (Interviewee 3375)
- Having someone unrelated to the product carry out testing can reveal undiscovered biases

5.4.4 Proposed new visual testing tool

Based on the experts' comments about important aspects of prototype testing and suggestions for improving the tool, the following changes are suggested:

- **Modularisation:** To increase the tool's flexibility and make it more generally applicable, it's elements should be modular, so that the user can combine them for their individual project. All elements of the existing visual tool, plus additional elements recommended by the interviewees, are entered into a 'module-table', containing terminology, symbols, a variety of basic visual PD process models, iteration arrows, types of tests, and test methods. Each aspect is discussed with regard to its importance for PD and prototype testing.

- **Layering:** To enhance the tool's utility for communication purposes, its depth of information should be increased while simultaneously reducing its visual complexity. To achieve this, it is recommended to create a visualisation with multiple layers. With the basic PD process model of the user's choosing as basic layer, additional layers can be drawn over this basic layer. For example, one layer could contain arrows depicting the flow of information, while another layer contains cost considerations.
- A **step-by-step guide** leads the user to draw elements from the module-table to produce a bespoke visualisation of their process plan and testing strategy.

A draft of the module-table and guide are found in the Appendix (Section 5.9).

In this proposed new testing tool, the expert's recommendations are combined: On a primary layer, the applied PD process model is depicted, onto which various layers can be added. Each layer contains different elements of an overall testing strategy for the particular project. In this manner, the visualisation can be kept simple for the purpose of communication. For the purpose of planning, however, additional layers can be added to display numerous types of information in varying levels of detail. This makes the tool highly customisable and thus generally applicable to a broad variety of PD projects.

In its simplest form, this tool could be used in a pen and paper based exercise, and the users draw their visualised testing strategy by hand. Using transparent film sheets, they could draw multiple layers of information onto a basic layer containing the general PD process model they follow. This could be particularly useful if the strategy is developed by multiple people.

A more elaborate format would be a computer software in which the user could drag and drop the various visual elements into their strategy visualisation. Additional useful information about the elements and different aspects of planning prototype tests could be shown in separate windows, and multiple layers could either be displayed individually, on top of each other, or in parallel. This approach could also be used by a group, but might require the use of a projector or large screen.

Testing the new tool's usability in a focus group

At an international conference about water and development, a workshop presented the amended tool as shown in the Appendix (Section 5.9), and three groups of participants used it to hand-draw a basic visual testing strategy for three simple case studies. The groups were given blank sheets of paper, various coloured pens, and transparent document sleeves, to allow the drawing of layers. Four researchers observed the group work and recorded their observations.

Group 1 / Case Study 1: The group discussion mainly focused on the development of non-sewered sanitation technologies rather than on the development of a testing strategy. Two researchers noted that the case study appeared to be not focused enough to provide guidance for the group work. Ultimately, under the lead of one of the researchers, the group produced a simple basic layer using a process model similar to the one depicted in Figure 5-1, and an additional layer depicting information flow arrows.

Group 2 / Case Study 2: The group had an engaged continuous discussion, and the information from the tool gave prompts to maintain the conversation. However, two researchers noted that the case study appeared too simple to necessitate the drawing of a complete testing strategy. Nonetheless, the group produced a simple drawing of their strategic approach to develop the handwashing station.

Group 3 / Case Study 3: At first, the group seemed to be overwhelmed with the information given in the module-table. Participants mentioned that following the step-by-step guide was difficult. Toward the end of the group exercise, a new participant with experience in software development joined this group and provided some guidance. The group produced two drawings of visualised testing strategies, one for software and one for hardware. The hardware-strategy followed the model from Figure 5-1, whereas the software strategy followed a spiral model (Boehm, 1988) as basic layer.

Thus, all three groups produced simple visualisations of testing strategies for the given case studies, which was seen as a success. However, when presenting their group's work, participants from all three groups noted that following the tool was quite complicated. One researcher remarked that only few participants had a background in PD, which made it difficult for them to understand the tool and join the discussion. Those participants who joined the discussions noted that they felt they learned a lot from the group work, and that they saw a benefit in using a flexible tool to think about how to specifically develop and test products. All researchers remarked that the case studies could have been described more clearly and provided more information for the groups.

5.5 Discussion

The ten interviewed experts gave rich accounts of their experience of developing products and planning and conducting prototype tests, as well as valuable comments about the visual test planning tool. Their responses were aggregated, categorised, and will be discussed below, followed by a discussion of the methodological approach.

5.5.1 Discussion of results

Communication was mentioned by nine out of ten interviewees to be an important aspect, but also a challenge in prototype testing. Successful, effective communication is crucial in projects involving multiple people, and PD projects tend to be a collaboration of numerous stakeholders. In order to develop the right product, the customer's vision must be clearly communicated, and test strategies, resources required for testing, and testing outcomes need to be understood by all stakeholders to set the right expectations. This observation matched our rationale for developing a visual testing tool (Hennigs, Parker, *et al.*, 2019b) and other existing research findings about communication in design and product development processes: Eckert et al. (2013) research the role of formality in design communication and describe the difficulties of communicating across disciplines. Similarly, Kleinsmann and Valkenburg (2008) discovered that avoidable iteration loops and lower quality in the final product could be caused by the lack of a shared understanding in co-design teams. They describe problems of communication and cooperation based on teams using different jargon and design representations and recommend addressing barriers to communication at an organisational level. A particular problem with communicating testing activities is the fact that testing is often under-appreciated, as was mentioned by several experts. For instance, a thorough study by Tahera, Eckert and Earl (2015) identifies a gap in the academic literature about interactions between testing and design activities and points toward PD process models, which often only present testing as part of a late-stage validation process, neglecting the importance of testing throughout the whole PD process. If common process models under-appreciate testing, it is difficult for test engineers to communicate their work well to colleagues. Another publication also found communication problems between disciplines based on the lack of a common ground, and recommended the use of *boundary objects* to mitigate these problems (Vincent, Li and Blandford, 2014). Boundary objects, also mentioned as possible solution to hindered communication by Eckert et al. (2013), are a concept developed by Star (1989) in the field of artificial intelligence. Star (1989) defines them as "*objects that 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*", and mentions "*objects devised as methods of common communication across dispersed work groups*" as one example.

Thus, such a boundary object could be a visualised testing tool, which a majority of respondents thought could aid in communication, help set expectations, and ensure stakeholder support. Verovšek et al. (2013), for example, describe the successful use of visual language for interdisciplinary communication in urban development. They investigated how to best communicate spatial relationships of urban spaces to the general public in order to improve their involvement into decision-making processes for urban planning. One of their findings was that more generic visual representations enable information to be presented more repeatably, comparably and generalised. Hence, simple visualisations are more likely to be effective boundary objects, a finding which also supports the observations of Keller et al. (2006), who developed a tool to visualise PD processes in engineering design to facilitate communication. They combined multiple types of PD process visualisations, like Gantt charts, Design Structure Matrices, and confidence profile plots in a single software tool, allowing the user to better understand all aspects of the project. This approach runs in a similar vein to the layering proposed here. Keller et al. (2006) argue that different visualisations offer different perspectives, and a combination of these allows the user to find perspectives that would stay hidden in the individual visualisations. In addition, it is likely conceivable that different people, particularly from different disciplines, view the same visualisation differently to others. This effect could be *diluted* by using more than one visualisation. This approach of combining multiple visualisations has been reported before in various fields (Unwin, 1999; Baldonado, Woodruff and Kuchinsky, 2000; Packham and Denham, 2003; Jarratt *et al.*, 2004; Browning, 2009, 2014), but the application to testing of prototypes appears to be novel. The modularisation recommended by some interviewees would be an additional advantage for professionals from various disciplines to use the presented tool, for example to use company-internal terminology.

Like communication, strategic planning was similarly seen as an important and difficult aspect of prototype testing. Having a strategy to testing prototypes allows for more confident communication, more targeted tests, as well as less wasted time and resources. Well-planned and well-documented tests will have a better chance of producing valuable results, which can inform the product's design and future tests. However, as several experts mentioned, planning is not always easy, and projects often diverge from their plans (Kattwinkel *et al.*, 2016). Four of the interviewed experts thought a visual tool could help in creating and maintaining a strategic plan for testing prototypes. While there have been ample attempts at developing prototyping strategies (Christie *et al.*, 2012; Camburn *et al.*, 2015; Menold, Jablokow and Simpson, 2017), these tend to focus on what prototypes to build, rather than how to test them. The less-prevalent publications describing testing strategies (e.g. Khalaf, 2006; Qian et al., 2010) tend to use mathematical models to optimise at what time during the PD process to test. Using a modular tool to develop bespoke visual testing strategies, however, appears to be a novel approach.

While it may seem obvious to some readers that communication and planning are important aspects of PD projects, and by association of testing prototypes, it is worth pointing out that being obvious does not make these aspects easy. As can be gauged from the previous paragraphs, there is a wealth of academic literature discussing these aspects just within the context of PD, from which only a few publications are referenced. Yet, they continue to be problematic issues in the eyes of the experts. Similarly, the advice of some experts to embrace failure and learn from it may seem self-evident. Nonetheless, it appears that a positive attitude towards failure continues to be advocated for, and its lack continues to be lamented (Matus, 2002; Jerrard and Barnes, 2006; Blank, 2011; Robbins *et al.*, 2012; Goldberg, 2019), indicating that, despite its obviousness, the concept remains difficult to grasp by practitioners. Thus, one should welcome a tool that can facilitate communication and planning of prototype tests, and frame failure as a necessary part of learning through iteration. As was mentioned by one expert, the intellectual property of knowing how to test prototypes in PD can be a valuable resource, and may offer commercial opportunities in the light of the apparent lack of formalised expertise in this field.

The experts' recommendations for generalising the tool and improving its utility were followed in two major aspects, namely modularisation and layering. By providing the user of the tool the components to build their own visualised testing strategy in multiple layers, rather than with just a rigid flow chart, the potential range of uses should increase considerably. The first trial of the revised tool proved moderately successful. While all three groups produced some sort of visualisation, there was a lot of confusion and participants remarked how complicated the exercise was. Nonetheless, the fact that unexperienced users could grasp the general approach of using the tool in the course of a 90-minute workshop is promising. Future work should aim at further improving and validating the tool's usability in a more practical context, for example in a case study. Trials with participants who are experienced in planning and conducting prototype tests could provide valuable information for the future development of the tool. It may become apparent that the step-by-step guide needs further elaboration to facilitate the use of the tool. Implementation of the tool into a simple software with drag-and-drop functionality could enable large-scale user testing via the internet.

5.5.2 Limitations to the methodological approach

The methodology applied in this study was of a qualitative nature. Therefore, its results cannot claim to be objective truth. Time constraints and access to professional networks limited the pool of potential interviewees, and while many large companies were contacted, none of them agreed to participate in the study. Six of the interviewees are personal contacts of the research team. It is likely that there exists an abundance of established knowledge, potentially highly formalised, about prototyping and testing strategies within such large companies, and we regret not to have gained access to this knowledge.

Nonetheless, the applied purposive sampling approach targeted interviewees with as varied backgrounds as was achievable, and other studies conducting expert interviews use similar approaches (Hauer, Harte and Kacemi, 2018; Majid *et al.*, 2019; Mejias and Banaji, 2019; Yusof *et al.*, 2019). Almost all respondents seemed to agree on a fundamental level on the importance of communication and thorough planning, on the need for flexibility during a project and between projects, and that a modular, visual tool could facilitate the prototyping process. This hints at the possibility that additional interviewees would have given similar answers.

The study attempted to draw upon tacit knowledge of experts in the field of prototype testing. This was necessary as a large portion of knowledge in this field, as well as in the wider field of PD is of a tacit, non-formalised nature, often gained through years of practical experience (Goffin and Koners, 2011). Research encourages the use, but also the transfer of tacit knowledge (Goffin and Koners, 2011), for example by externalising it into process models (Flanagan, Eckert and Clarkson, 2007), or by providing a favourable workspace that facilitates the sharing of tacit knowledge (Penciuc, Abel and Van Den Abeele, 2013). We follow a similar goal by creating a tool that enables its users to visualise and share their knowledge.

The combined deductive-inductive approach to analysing the transcripts seemed appropriate, given the aim of the study. The research questions were clearly defined and aimed at learning about prototype testing in general and the visual planning tool in particular. Thus, querying the transcripts for these questions in a deductive manner was sensible. The following inductive development of sub-categories then yielded a well-structured image of the expert's responses.

The focus group exercise, aimed at assessing first time user responses for the revised tool, did prove underdeveloped. The case studies were too short and of either too high or too low complexity for the given timeframe. More appropriate case studies could have been developed to ensure the exercise could be carried out in the given time. Had the trial been organised independently from a conference, more time would have been allocated for both the introduction to the tool and the group work. The exercise was further complicated by the fact that most participants had no experience in PD, let alone in testing prototypes. This can be attributed to the context in which it was held. A focus group held in a different context would have targeted more suitable participants. With the given complications, the observed difficulties participants had during the exercise could neither be assigned to nor fully disconnected from the tool. Another focus group, with more time allocation and selected participants, could provide more reliable results.

5.6 Conclusions

The present study could expand the knowledge about important aspects of and barriers to effective prototype testing, with communication and strategic planning being the most important. It therefore seems reasonable to further attempt to facilitate communication and planning of prototype tests.

Evidence for the usefulness of a visual testing tool for communication and planning purposes could be established, and the recommendations for generalising and improving the original tool were considered in the development of the modular layered tool presented in the Appendix (Section 5.9).

The first trial of the revised tool showed promising results, but could neither prove nor disprove whether the tool could be useful in practical application. Thus, future research would need to validate the new tool's usefulness in a larger study. Should this be established, a more formalised version, potentially as a software, could be developed to further enhance its flexibility.

A tool as presented in this study could enable its users to share their tacit knowledge, and communicate and plan prototype tests more effectively. This could result in more efficient use of resources and higher information yield from prototype tests. With its improved generalisability, the tool may find application in a wide field of various PD projects.

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5.8 References

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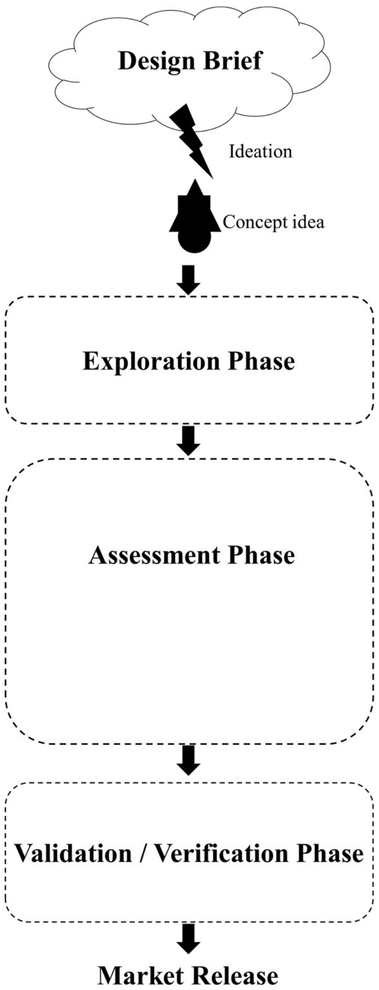
5.9 Appendix

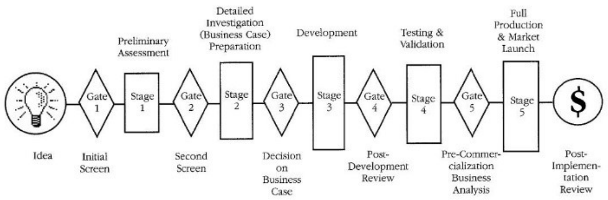
5.9.1 Appendix A: Steps to draw a bespoke testing strategy visualisation

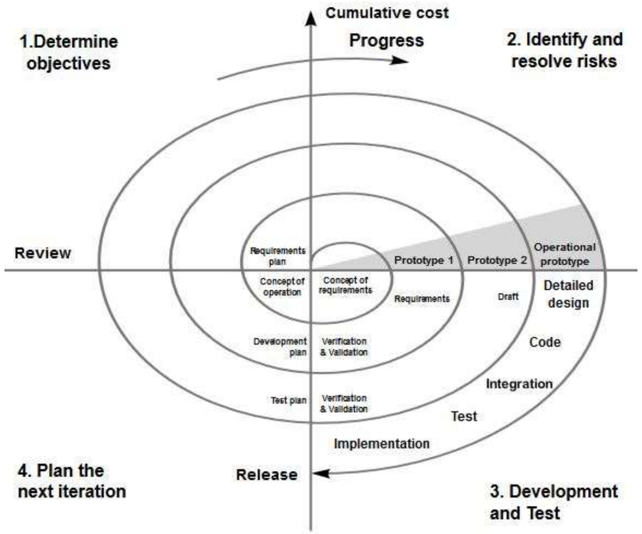
1. What is your general PD process model? Does your company follow an established process? If not, there are process models in the table to choose from.
2. Are you developing a front end, a back end, or both? If both, you might want to split your process model into two paths that converge at the point of prototype integration. Consider where the two would interact for testing purposes.
3. Are you developing software, hardware, or both? If both, you might want to draw two process streams for the individual developments. Consider where the two would interact for testing purposes.
4. Draw the outline of your project process model. This is the basic layer of your testing strategy visualisation.
5. Consider risks
    a. What are the main risks (e.g. customer adoption / marketability, health and safety, technological risks, financial risks, delays, and reputational risks, etc.)?
    b. Consider time constraints
    c. Consider budget constraints
6. What needs to be done to reduce the major risks? What prototype tests are most important? At what point of the development should they occur.
7. Draw out the plan. You can add additional elements to the basic layer or add additional layers. If one layer becomes too complex, it loses value as simple communication tool. There are elements to choose from in the table, but you are free to add bespoke elements as necessary.
8. Throughout the PD, you can refer to and adapt the visualisation. It is not a rigid plan and should be amended if the situation demands it.

Table 5-3: Module-table of visual elements.

	Elements	Details
Process models	These form the backbone of the testing strategy visualisation	

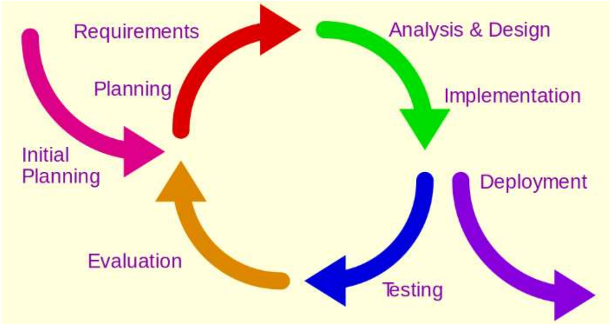
	Elements	Details
		The **three phases model** (Hennigs, Parker, *et al.*, 2019a) shown here was used for the first iteration of the visual test planning tool. It is based on a description of different types of usability tests throughout product development by Rubin and Chisnell (2008). It divides prototype tests into three distinct phases: The objective of the exploration phase is to explore potential solutions to the design brief, to discard unviable ones, and to gather an understanding of the required development process, i.e. to develop the questions that need to be answered in the assessment phase. The objective of the assessment phase is to expand the knowledge about the potential product solutions, to answer the questions developed in the exploration phase. The outcome of this phase should be one single, functional prototype. The objective of the verification and validation phase is to ensure that all questions have been answered, that the product functions as expected and is, in fact, a solution to the design brief.

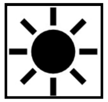
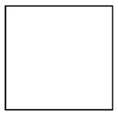
	Elements	Details
	Figure 2 **An Overview of a Stage-Gate System** 	The stage-gate process, as described by Cooper (1990), is: “both a conceptual and an operational model for moving a new product from idea to launch. […] A process is sub-divided into a number of work stations. Between each work station or stage, there is a quality control checkpoint or gate.” This model provides a high degree of structure throughout the PD process. Image source: (Cooper, 1990)

<table>
<tr><th></th><th>Elements</th><th>Details</th></tr>
<tr><td></td><td>
</td><td>The spiral model (Boehm, 1988) is a risk-driven process model that
- “Fosters the development of specifications that are not necessarily uniform, exhaustive, or formal, in that they defer detailed elaboration of low-risk software elements and avoid unnecessary breakage in their design until the high-risk elements of the design are stabilized.
- Incorporates prototyping as a risk-reduction option at any stage of development. In fact, prototyping and reuse risk analyses were often used in the process of going from detailed design into code.
- Accommodates reworks or go-backs to earlier stages as more attractive alternatives are identified or as new risk issues need resolution.” (Boehm, 1988)

“The primary advantage of the spiral model is that its range of options accommodates the good features of existing software process models, while its risk- driven approach avoids many of their difficulties.” (Boehm, 1988)

Image source:
https://commons.wikimedia.org/wiki/File:Spiral_model_(Boehm,_1988).svg; based on (Boehm, 1988)</td></tr>
</table>

	Elements	Details
		The **iterative design model** was first used in software development, first described by Gossain and Anderson (1990), but has since been adopted in other PD projects, from user interfaces (Nielsen, 1993) to novel devices for children with disabilities (Thomann *et al.*, 2017). This model focuses mainly on the design aspects of PD. Image source: https://commons.wikimedia.org/w/index.php?curid=34159246; author: Aflafla1; license: CC0 1.0 Universal Public Domain Dedication
Types of tests		
		**User testing** is any kind of testing that involves future users of the product in development. Often, user testing is collecting qualitative data to understand what users like and dislike about the product, and how they interact with it (Rubin and Chisnell, 2008).
		**Laboratory testing** is testing that simulates the environmental conditions or usage scenarios of a product to maintain better control over these conditions. It can also be classic laboratory research (Hennigs, Parker, *et al.*, 2019b).

	Elements	Details
		**Field testing** encompasses all tests that expose prototypes to the actual environment in which the product will be used (Hennigs, Parker, *et al.*, 2019b).
Prototypes		
		**Generic prototype symbol** – If you don't yet know what the prototypes will look like, which is likely to be the case before starting the project, simply use a generic symbol.
		Once you have developed them, adding images of your actual prototypes can be a way to celebrate these milestones. If you plan on doing this, leave space in your visualisation for such images.

	Elements	**Details**
Elements to consider		

<table>
<tr>
<td></td>
<td>DOE</td>
<td>“Based on the work of statistician R.A. Fisher (Yates, 1964; Fisher Box, 1980), the Design if Experiments (DOE) uses statistical approaches to minimise the time and effort required for a set of experiments while maximising the validity, reliability, and replicability of information gathered from them. The basic principles of DOE, initially developed for agricultural research, are (Fisher, 1935; Cortes, Simpson and Parker, 2018):

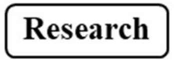
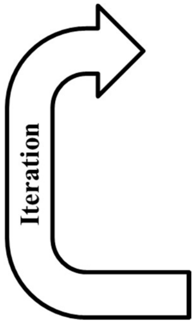
Factorisation: the variation of several experimental factors at once in order to reduce the number of experiments to run.
Replication: the repetition of an experiment with the same settings for experimental factors (treatments) in order to estimate the experimental error.
Randomisation: the random application of treatments and order in which experiments are run, to validate the assumption that the observations and errors are independently distributed variables.
Local control of error, or blocking: the subdivision of experimental runs into homogenous blocks in the attempt to lessen the impact of errors introduced by controllable nuisance factors, e.g. male and female patients in medical drug trials.

It may occur that these principles have to be compromised to some extent for practical reasons, or that complex processes are to be investigated. Within the DOE-toolbox are methods such as split-plot design (Lee Ho, Vivacqua and Santos De Pinho, 2016; Kulahci and Tyssedal, 2017), fractional factorial design, response surface methodology, and random effects models (Montgomery, 2009) for such cases. It is thus possible to</td>
</tr>
</table>

	Elements	**Details**
		achieve a high level of understanding from comparably few experimental runs.” (Hennigs, Parker, *et al.*, 2019b)
	UCD	The term ‘User Centred Design’ (**UCD**), first coined and publicised by Norman and Draper (1986) in the context of software design, encompasses a collection of processes and methodologies that follow the basic principles of a human-centred approach: • “The design is based upon an explicit understanding of users, tasks and environments. • Users are involved throughout design and development. • The design is driven and refined by user-centred evaluation. • The process is iterative. • The design addresses the whole user experience. • The design team includes multidisciplinary skills and perspectives. “ ISO 9241-210:2010 (ISO, 2010) Excerpt from (Hennigs, Parker, *et al.*, 2019b)

	Elements	Details
	REL DUR	“**Reliability** estimation, a part of reliability engineering, comprises reliability tests and the analysis of the data gathered in those tests. Kapur and Pecht (2014) define reliability as “the ability of a product to function properly within specified performance limits for a specified period of time, under the life-cycle application conditions”, i.e., how long a product functions without needing repair. This means that reliability tests are carried out to assess the likelihood of the product—or its components—failing over time. They are usually conducted on prototypes of high maturity, on randomly selected products fresh off the assembly line, or even products that have been in use for a certain time. Similar to DOE, statistical approaches are used to calculate a level of confidence with which a failure will occur in a given time. **Durability** is a measure of a product’s lifetime, i.e. the how long the product can be used until repairs become more expensive than replacing it (Garvin, 1996). In other words, durability is a particular aspect of reliability (Tahera *et al.*, 2019). This implies that, while the calculation of durability will involve repair costs and other economic factors, the durability tests to assess likelihood of failure will often be similar or identical to reliability tests.” *Excerpts taken from* (Hennigs, Parker, *et al.*, 2019b)

	Elements	Details
	Int std	“International technical **standards** are established norms or requirements applied to technical systems. They are a crucial aspect of almost all industries. They play an important role in technology development by providing a benchmark for quality and acceptability in the market place and guidance on the safety, reliability, efficiency and interchangeability of products. The testing procedures and performance requirements outlined in technology standards form the basis for the process of ensuring a product is compliant with the standard before being released to market. This does, however, not mean that the first time the standard should be consulted is at the end of the PD process. Instead, the performance, safety and other requirements provide the benchmark to which even early prototypes can be compared, and the testing procedures and-protocols can be adapted or used directly to test prototypes of sufficient technological maturity.” *Excerpt taken from* (Hennigs, Parker, *et al.*, 2019b)
	H’nS	**Health and safety** considerations should always take priority in planning prototype tests. In the case of new medical products, for example, tests with real patients should only be conducted if the risk of their health and safety being affected negatively is negligible.

	Elements	Details
		**Researching** existing solutions within industry can be a fast and cheap alternative to designing and testing components and trying to reinvent the wheel. If time constraints permit it, research should be included in the earliest stages of design.
		"**Iteration** may occur throughout the PD process and can have different causes and outcomes (Wynn and Eckert, 2017). It can be welcomed as a driver of positive design change, or seen as a wasteful, costly delay in a PD project (Ballard, 2000; Le, Wynn and Clarkson, 2010; Wynn and Eckert, 2017). For the development of a visual testing strategy it is mainly important to know that, while iterative loops can occur throughout the PD process, they value for cost reduces as product maturity increases (Wynn and Eckert, 2017), and to consider which test results should trigger or prevent an iterative loop. With the main goal of the PD process being a marketable product, any proof that a prototype does not represent such a marketable product should be a trigger of iteration. Failed tests, like the shortfall against benchmark values, can be seen as such a proof. Cost is another deciding factor and will have to be considered by a project manager when deciding whether to iterate further or not." *Excerpt taken from* (Hennigs, Parker, *et al.*, 2019b)

	Elements	Details
		**Information flow** is a crucial aspect of prototyping. The quality of prototype tests and their results depends on well-communicated information needs of the designers. Vice versa, sensible design changes rely on well-communicated test results.
		For the aim of effectively analysing tests and test results, but also for communication and reporting purposes, **documentation** is a critical aspect of prototype testing. Examples of documentation types can vary from notes to digital spreadsheets to photographs with accompanying notes.
		**Cost** tends to increase as the project progresses and the product's maturity increases. Simple visualisations can help signify the increase in cost, e.g. for building prototypes.

	Elements	Details
	Risk	There are various **risks** in product development. Reducing the major risks of a PD project is one of the main motives for prototype testing. Some of the biggest risks in prototyping are customer adoption, health and safety, technological risks, financial risks, delays, and reputational risks. Identifying the biggest risks to a PD project will drive decision processes toward the most important tests.

5.9.2 Appendix B: Codebook of interview Analysis

Table 5-4: Full codebook of the codes and categories created for the interview analysis. Indented codes are subsumed under the next less indented code above.

Name	Files	References
Category A Important Aspects of prototype test planning	0	0
Are tests separate or one domain	0	0
Tests are one domain	0	0
tests become tightly linked for mature prototypes	3	3
tests have to be combined if human input for functionality cannot be simulated	1	1
Tests are separate	1	1
Front end and back end are separate	1	1
tests are separate for early component level prototypes	3	3
Tests are separated according to priority	1	1
Communication is important	3	5
Continuous feedback communication with customer is important	3	6
Problem Communication is difficult	5	8
communication is less difficult within one company	1	1
companies do lots of testing but little theory about it exists	2	2
big companies will have more stringent processes	1	2
start-ups and small companies have less defined processes	2	3
start-ups mostly do RnD and market research	1	1

Name	Files	References
companies will outsource testing if they don’t have the equipment	1	1
coordinating with many people or groups is difficult	1	1
hardware and software often developed by different people	1	1
hardware software allow for very different development cycles and speeds	1	1
software may only be developable after hardware electronics are completed	1	1
coordinating with other companies processes is difficult	1	2
Expectations are a problem	3	6
Testing is underappreciated	3	9
scientific method can be a good approach to avoid over-positivation of results	1	1
documentation of testing progress and results	6	6
Hardware Software Spectrum	3	7
Software is often delivered unfinished	3	3
software iterations can occur after roll out	3	3
software testing can be automated	1	1
iterations are important	2	2
Flexibility is important	4	5
multiple iterations of working designs can be developed without deciding on one solution	1	1
Electronics companies may not iterate at all	1	1
Problem Iterating is expensive	0	0

Name	Files	References
Finding problems can entail a large iteration loop	1	1
iteration is like canoeing you only go back to last fork	1	1
Problem budget constraints may restrict no of iterations	2	5
rapid prototyping early on is important	2	2
Learning from Test results	0	0
analysing tests thoroughly is important	2	3
Finding faults during testing is perceived as a good thing	3	3
qualitative and quantitative testing both have a lot of value	2	2
using test results to design future tests is important	2	3
Risk reduction	0	0
Prioritising problems according to severity or risk	2	5
Problem Risk of high investment before having test results	0	0
anticipating test outcomes can be impossible until the prototype is fully functioning e.g. for electronics	1	1
building an electronics prototype means designing a manufacturable product	1	1
necessary market research may require field user tests with fairly mature functioning prototype	1	2
risk mitigation is an important part of why testing is done	2	3
risk reduction is crucial for most PD projects	1	1
Strategic Planning of Tests	0	0
a strategic approach is important	1	3

Name	Files	References
anticipating test outcomes and actions for failed tests	1	1
building the prototype to fit the test is important	3	4
considering resources is important for planning	1	1
defining a clear test question is important	6	7
defining clear failure criteria is important for test planning	1	1
good test design and execution is important	1	1
Planning ahead is important	2	2
planning becomes important in later development stages	1	1
Problem test planning can be difficult	0	0
avoiding to test when unsure if test will pass is a problem	1	1
deciding which tests are necessary can be difficult	1	1
finding the right measurands can be difficult	1	1
losing sight of bigger picture can yield unnecessary tests	1	1
tests can reveal new questions	1	1
unanticipated tests can be executed badly	1	1
unclear design brief can yield unclear test design	1	1
novel products lack technical requirements precedent or international standards	1	1
novel products require novel development of test protocols	1	1
testing protocols are part of IP thought leadership and important part of innovation	1	1

Name	Files	References
testing the protocols can take more time than testing the prototype	1	1
Understanding the scope of testing is important	2	2
user tests should be done with actual users	2	2
using test protocols of similar products can be a good starting point	1	1
using the right approaches for what you're trying to learn is important	2	4
Timing is important	2	6
coordinating timing of resources is important	4	5
Problem timing is difficult	5	9
prototyping electronics is very expensive and slow	1	1
electronics dev is not very agile	1	1
Category B How a visual tool could add value to planning prototype tests	0	0
Is a visual tool a useful thing	0	0
tool could help improve communication	0	0
tool could help raise appreciation for testing	3	3
Tool could help set expectations	1	1
tool could help with stakeholder engagement	4	4
tool could help plan tests	2	2
if a tool could remind you not to avoid difficult tests, that would be good	1	1
modular version of the tool could be useful to provide ideas to then build bespoke process	1	1

Name	Files	References
tool can help plan tests with future project process in mind	2	2
tool could help plan tests with other product parts in mind e.g. front end back end	1	1
tool could provide structure	2	4
tool could be useful for training new staff	2	2
positive comments	0	0
like considering international standards is a good idea	4	5
like considering multiple aspects	1	1
Like dotted line to signify separation connection ambiguity between front end and back end	1	1
like iteration possible arrows at multiple places	2	2
this is close to my understanding of the process	6	6
Category C How the tool could be improved	0	0
Considerations that should be highlighted	4	4
design and testing for manufacture from early on is important	1	1
health and safety risk evaluation can be crucial for test planning	1	1
industry research can yield existing solutions to avoid unnecessary testing failures	1	1
it can be useful to have a tester unrelated to the project	1	1
Extra Layers	8	20
add test outcomes	1	1
cost considerations could be added but are difficult to generalise	1	2

Name	Files	References
focus of phases should be highlighted	1	1
information flow not depicted	3	5
more explanation should be given for all aspects	2	3
option to add examples or photos of prototypes is missing	1	1
option to visualise progress status would be useful	2	2
other layers could be added	1	1
risk should be considered	1	2
specification matrix is common tool for electronics testing	1	1
tool could be useful for showing specification matrix on detailed layer	1	1
Graphic presentation	6	12
colour missing	1	1
flow chart could be more graphically pleasing	1	1
process shape should be circular	1	2
Not all elements are described in legend	6	6
visualisation looks more complex than my process	2	2
Iteration	7	11
iteration arrows could better be shown as branched arrows	1	1
iteration arrows not symmetric	1	1
iteration loops sometimes don’t complete the loop (micro-iterations)	1	1
iteration much less likely for electronics development	1	1
iteration should feed back into design concept at the top	2	2

Name	Files	References
iteration too much especially late in process	3	5
Modularisation	9	33
additional level of testing between prototype and product is pilot testing	1	1
process doesn't fully align with interviewees process	4	4
back end front end integration would occur earlier or later	1	2
consider durability	1	1
consolidate terms HALT ALT and Reliability	1	1
Flexibility could be enhanced to account for different projects	4	4
more back end front end interaction early on already in exploration	1	1
symbols don't fully align with interviewees field	2	2
terminology needs to be adjusted or changeable	6	12
user testing UCD should be considered for back end early on as well	1	1
every product is different so generalisation impossible	1	1
physical prototyping can be used in ideation processes already	1	1
there are different levels of testing (component subsystem system)	2	2

6 Discussion and Conclusions

Abbreviations: BMGF – Bill & Melinda Gates Foundation; NMT – Nano Membrane Toilet; PD – Product Development; SMF – Synthetic Menstrual Fluid

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The work for this thesis was part of a large, complex, interdisciplinary project that is still ongoing: At the time of writing this chapter, the website http://www.nanomembranetoilet.org lists 58 former and current team members. The NMT had already been invented in concept, and its components underwent further development and refinement while the work presented here was carried out. Based on the work of the many people involved in the NMT project, all components will be refined, eventually integrated into the whole system, and finally released to market. Thus, the presented work constitutes only one of many contributions for the development of the NMT. Just like all cogs of a machine have to work for the machine to function, all contributions to the project are essential for the project to succeed. By providing a tool to facilitate the communication between teams, this thesis may provide the lubricant for the other cogs to turn with less friction.

The aims of this thesis were a) to plan and conduct prototype tests, thus generating data to inform the further development of the NMT, and b) to investigate and formalise how prototype tests are planned and conducted for the NMT and other novel, complex products. With these aims in mind, the contributions to knowledge generated in chapters 2 to 5 and summarised in Table 6-1 can be divided into two general categories: knowledge about sanitation systems, and knowledge about testing of prototypes. Both categories contain contributions specific to the NMT project, and those that are more generally applicable.

Table 6-1: Summary of contributions to knowledge made within this thesis

Key areas of data produced from the thesis	Observational data from functionality tests; photographs from swipe tests & settling/displacement tests; numerical data from image analysis; interview transcripts; user survey questionnaires; water quality parameters from settling tests

Methods that are new or tested in a new context	User tests of NMT prototype (including interviews and survey questionnaires); swipe tests including image analysis; a recipe for synthetic menstrual fluid; settling/displacement tests of faeces and toilet paper in small-volume containers; a visual flow chart to aid in communication and planning of NMT prototype tests; a generalised modular tool to develop visual testing strategies for PD
Elements of thinking or experience from the present work that are transferrable to other contexts	The perception of cleanliness depends on various factors; user acceptance is crucial to the success of a new product; prototype testing programmes are part of an iterative process and developing them is in itself iterative; each PD process is unique and likely requires a bespoke prototype testing strategy

In the following sections, the findings are discussed with regard to their meaning for the NMT project and for general research and practice.

6.1 Knowledge about sanitation systems in general and the Nano Membrane Toilet in particular

As mentioned above, Chapters 2 and 4 both yielded valuable knowledge about the NMT that could be translated into design recommendations for future iterations. From the tests described in Chapter 2, recommendations were made to change the geometry of the toilet pan, and how to better operate the mechanical flush in order to maintain its cleanliness. Tierney (2017) developed the flush and thus provided the basis for the conducted field tests with real users and real faecal material, which could validate and extend his work. It was also found that the perception of cleanliness is an important factor for users of sanitation systems. Other studies highlight the importance of perceived cleanliness (Vos *et al.*, 2018a), and clean toilets are a major factor in improving the perception of cleanliness in the Netherlands (Vos *et al.*, 2018b). Jenkins and Curtis (2005) found the desire to improve cleanliness to be a driver for rural villagers in Benin to move from open defecation to pit latrine use, and Curtis and Biran (2001) propose that disgust and hygienic behaviour have developed evolutionarily to protect the human body from pathogens. Thus, this finding was a useful validation of existing knowledge and extended it to apply to novel waterless sanitation technologies. With promising ongoing research into faeces-repelling surface coatings (Wang *et al.*, 2019), it is likely that a dry toilet flush could quickly be perceived as clean as a water flush toilet and therefore find application in dry sanitation technologies. It can be expected that users will still have to apply small amounts of water or a toilet brush to maintain a dry flush, but this is also common with water flush toilets.

Tierney's (2017) methodology of using imageJ software to compare faeces removal rates in the NMT rotating bowl could be confirmed to be effective, while its limitations were also acknowledged. Similarly, the recipe for synthetic faeces by Penn *et al.* (2018) was validated, with the added simplifications of using peanut oil instead of oleic acid and producing one batch of material from which samples of other moisture contents and density were produced by adding water and baker's yeast respectively. The fact that the addition of baker's yeast was enough to make synthetic faeces float affirms the observation of Levitt and Duane (1972) and (Cruddas *et al.*, 2015) that it is the gas content rather than fat content that causes faeces to float. However, the observations from Chapter 4 highlight that toilet paper kept faeces afloat, regardless of gas content. This appears to be a novel observation that has not been described in academic literature. For the NMT and similar sanitation systems, this means that solid-liquid separation cannot be achieved by settling alone, if toilet paper is added. Since many of the reinvented toilet systems treat solid and liquid wastes separately (BMGF, 2018), effective phase separation is crucial for successful treatment of both waste streams. Potentially, all solids would settle after maceration. Therefore, the effects of maceration on settling and chemical quality of the liquid fraction in the NMT collection tank are another promising object of future research.

The recipe for synthetic menstrual fluid (SMF) is a novel contribution that could find application in other studies researching the staining of menstrual fluid. While it proved useful and effective, it was not validated rigorously, and it would require further study to ensure it is an appropriate proxy. Given the substantial range of amount, colour, rheology, and composition of real menstrual fluid (Levin and

Wagner, 1986; Harlow and Ephross, 1995; Dasharathy *et al.*, 2012), it is just as difficult to produce an appropriate synthetic surrogate for it as it is for faeces. Future research could attempt a similarly thorough study on SMF as Penn *et al.* (2018) did for synthetic faeces.

The findings of Chapters 2 and 4 have implications for the design of the NMT and other novel non-sewered sanitation systems as a whole: First, to be adopted by users these toilets should be clean, or at least appear clean. To achieve a clean appearance, the toilet bowl must be free of faeces and bloodstains, so any flush, dry or wet, must be able to remove these stains sufficiently well. Second, to function properly, many reinvented toilets require well separated solid and liquid waste streams. Source separation, however, is not necessarily a viable option: While potential users tend to convey support for urine diversion toilets, many studies also report problems with cultural barriers, technical difficulties, and maintenance issues (Lienert and Larsen, 2010; Blume and Winker, 2011; Uddin *et al.*, 2014). Therefore, effective phase separation post-flush and pre-treatment should be investigated further.

6.2 Knowledge about testing prototypes of the Nano Membrane Toilet

In addition to the contributions to methodological knowledge described above, Chapters 2 and 4 also yielded theoretical knowledge about planning and conducting prototype tests, particularly when compared. The prototype tested for Chapter 2 was a highly developed prototype that largely looked and worked like the designers' vision of the final product. It was built without specific test procedure or expected test results in mind, but rather tested in various exploratory ways, both quantitatively and qualitatively. Hence, these tests produced a rich dataset, but also entailed considerable expenditures and coordination efforts. In contrast, the conical tank tested for Chapter 4 was a highly specialised prototype custom built for the specific set of tests conducted with it, which were carried out by a single researcher. Thus, cost and time spent on this study were noticeably less than for Chapter 2. While an increase of cost is common with prototypes of increased complexity (Boehm, 1988), it seems plausible that the strategic approach based on the visual flow chart developed in Chapter 3 contributed at least in part to a more efficient test design and execution: with a more holistic understanding of the NMT's PD process and of its information requirements, the tests were developed to address a specific question. Then, a bespoke prototype was built to conduct the tests. This strategic procedure was successful and efficient. As was learned in Chapter 5, a strategic approach and well-communicated tests are crucial to effective prototype testing. Therefore, it is recommended that future prototype tests for the NMT, and potentially all other products, are planned strategically and communicated across teams using a visualised testing strategy. This holds especially true as a product's maturity increases: for the example of the NMT, future PD efforts will likely involve commercial partners, tests will be conducted on more complex prototypes and involve more people from various teams, companies, and backgrounds. As this happens, the need for a simple visualisation of testing efforts to communicate across teams will likely increase.

Future research could test the effectiveness of a visual prototype testing flow chart as tool for improving communication in practice: As the next steps of the NMT development are planned, the flow chart developed in Chapter 2 could be presented to and discussed with all stakeholders. Alternatively, a more comprehensive multi-layered visualisation could be developed by the stakeholders in a group exercise, using the tool developed in Chapter 5. The use of this tool for developing a shared vocabulary and understanding of the project's aims would then be encouraged. Throughout the next phase of NMT development, the effectiveness of a visualisation for improving communication could be monitored through an ethnographic study, or simply by querying the stakeholders' perception of the tool's utility. This could be achieved using a simple questionnaire or short interviews. The results of such an assessment would only be qualitative, as any metric quantifying the improvement of communication would likely be arbitrary.

It is also worth reflecting on the ethical considerations one should make when conducting field tests of a novel sanitation technology in a country of the Global

South. As described in Chapter 1, it is these countries that are most affected by poor sanitation. A lot of reinvented toilets, and other technologies, have been, and continue to be tested there, often in low-income urban areas. This is done for important reasons: The inhabitants of these areas are the target user group of reinvented toilets (BMGF, 2018a), which need to be developed to fit their needs, aesthetic views, and toilet use habits. Accordingly, it seems only logical to test the toilets '*on*' them. However, this demands several considerations to ensure the dignity, safety, and rights of study participants remain unharmed. Research ethics guidelines will generally demand that written informed consent is obtained, which can be complicated by language barriers, low literacy, or cultural differences, and numerous studies address these problems (Rajaraman *et al.*, 2011; Bull, Farsides and Ayele, 2012; Addissie *et al.*, 2014; Embleton *et al.*, 2015). Beyond these 'formalities', the research on sanitation technologies demands a respectful conduct that honours the dignity and privacy of the study participants. It is all too easy to overstep personal boundaries in the pursuit of knowledge about toilet use behaviour, and researchers have to recognize and prevent such transgressions. Furthermore, they have to ensure the safety and reliability of the prototype they want to test. As is described in Chapter 2, the NMT front end prototypes were first tested in an institutional setting before they were deployed to households. If the first tests had revealed any issues with the safe and reliable operation of the flush, the second tests would have been postponed or cancelled. If a household agrees to have their toilet replaced with a prototype of a novel technology for several weeks, they extend a considerable amount of trust towards the researchers, which cannot be betrayed. It is therefore absolutely essential that the researchers make every effort to ensure the safety, dignity, and rights of the study participants! This is further complicated by the expectations that such a field trial can set in the participants: When they are given a new technology to test that is more comfortable, cleaner, or better looking than their usual toilet, it may be disappointing to have it taken away again at the end of the trial. Participants might feel 'used' when the researchers disappear after a few weeks and results are not communicated back to them. Thus, community involvement should be a consideration when planning research in low-income communities.

6.3 Knowledge about testing prototypes in PD projects

In addition to the applicability for the NMT project, Chapters 3 and 5 revealed interesting findings about prototype testing in general. Chapter 3 found a wealth of academic knowledge about various aspects of building prototypes, planning and modelling PD projects, and testing in general. It also revealed a lack of literature aiming at consolidating this knowledge to apply it to planning and conducting prototype tests for PD (Tahera, Eckert and Earl, 2015). With this gap in the literature, it was unsurprising, that the prototype tests in Chapter 2 were not planned strategically, but rather in an exploratory way. The visual flow chart presented in Chapter 3, an original contribution, proved useful for planning and conducting the tests in Chapter 4. Chapter 5 attempted to expand on the well-documented academic knowledge by exploring the tacit knowledge of PD practice, existing in the minds of product developers and, at best, in company-internal documents. While other studies have attempted to draw upon this knowledge in other aspects of PD, either through case studies (Flanagan, Eckert and Clarkson, 2007), or expert interviews (Goffin and Koners, 2011; Penciuc, Abel and Van Den Abeele, 2013), the focus on testing of prototypes is largely underexplored (Batliner *et al.*, 2018). The findings reflected our own experience of prototype testing: the two most important and simultaneously difficult aspects of prototype testing were good communication and a strategic approach: The better-planned and communicated tests of Chapter 4 could be carried out cheaper, quicker, and with fewer staff than the exploratory tests of Chapter 2. Besides the lack of formalised knowledge on how to create a prototype testing strategy, the requirements of funding bodies to demonstrate functionality as quickly as possible, or simply to “get on with it” in light of the urgency of the sanitation crisis, affect the decision-making process in a PD project like for the NMT. Had such external pressure not existed, the field testing described in Chapter 2 may have been conducted later, after a more thorough planning phase. Aside from this knowledge about prototype testing, the experts also provided valuable recommendations about the design of a visual test planning tool, which led to the modular, layered version of the tool presented at the end of Chapter 5. This tool, while only validated in a small trial, is based on extensive literature search of Chapter 3 and expert knowledge of Chapter 5. Hence, it is likely that future studies aimed at thorough validation of this tool will yield positive results. When developed further, for example into a computer-based tool, it could find application not only in the NMT project, but any sort of PD endeavour in need of structure.

6.4 Limitations in the overall methodological approach

This thesis about interdisciplinary work was in itself an interdisciplinary effort. Chapter 2 comprises qualitative methods like interviews and photography, and quantitative methods like surveys, image analysis, and mass balances. Chapter 3 reviews literature of multiple disciplines, like management, statistics, process modelling, and design and creates a synthesis of the reviewed literature in the form of a visual tool. Chapter 4 describes simple qualitative methods like photography and observation, as well as quantitative analytical methods like COD and solids measurements, which are then statistically analysed. Lastly, Chapter 5 is based on expert interviews that are qualitatively analysed. Interdisciplinary research is difficult, and prone to being appropriated by one dominating discipline (Brister, 2016; MacLeod and Nagatsu, 2018). While the first author has a background in process engineering, a discipline that combines several other engineering disciplines, this does not make him an expert in interdisciplinarity, nor in the other disciplines' methodologies. It is likely that research methods are not developed as well as they could have been by an expert in the respective field, and the contributions to knowledge, dispersed across disciplines, may be challenging to highlight. However, as presented in this thesis, the development of a complex product like the NMT is an endeavour that demands inputs from multiple disciplines, and it requires sufficient understanding of all of them to develop a tool to help members of the different disciplines communicate. Ergo, interdisciplinary problems require interdisciplinary solutions.

The research documented in this thesis was not planned as it is presented. The work for the thesis began only shortly before the field trials of Chapter 2 were due to begin, and there was not enough time to develop a comprehensive, literature-based testing strategy, nor to consider the future chapters of this thesis. Instead, the work had to be focused on developing tests and metrics of success to test an already developed prototype. The field trials and subsequent laboratory work yielded useful design recommendations, which made them a success for the project. However, given more time, it would have been beneficial for the overall research to develop a metric for the effectiveness and efficiency of the field trials, in order to compare them to the later prototype tests of Chapter 4. For example, this could have been a semi-quantitative measure of 'gained knowledge' versus time, money, and staff involved. This would have provided a way to determine quantitatively whether the use of a strategic approach improved the prototype testing process.

The redesign and development of a new prototype occurred while the research for Chapter 3 was still ongoing, and the testing flow chart therefore had little influence on the development process. As described in the preface to Chapter 3, this resulted in a prototype being built that, while of use for the NMT project, could not be used for tests within the scope of this thesis. Testing a new iteration of a similar prototype in Chapter 4 would have made it more easily comparable to Chapter 2. In this case, field trials that would have been similar to the work in Chapter 2, but with better planned testing protocols would have been carried out on a similar but improved prototype, designed specifically for these tests. Therefore, a comparison of 'knowledge gained' versus expenditure could have been far more appropriate. Had Chapter 3 been completed earlier, the visual flow chart could have found immediate application as tool for communication and planning of the redesigned prototype.

Chapter 5 yielded a wealth of rich, interesting information about testing prototypes in PD. Unfortunately, the research was only finished towards the completion of this thesis. Therefore, findings from the expert interviews and the resultant revised tool for planning prototype testing remain largely in the realm of theoretical knowledge and could not be validated thoroughly. Ideally, the interviews should have been conducted and analysed sooner, ideally before the planning of the tests in Chapter 4. This would have allowed validation of the tool's use in practice, rather than in a small trial with unexperienced participants.

With these considerations in mind, the approach for this thesis may have been as follows:

1. Begin literature review.
2. Plan tests for field trials and develop a metric measure the efficiency of these trials, including cost, time, and human resources.
3. Conduct and analyse the field trials and subsequent laboratory tests.
4. Communicate design change recommendations to the design team.
5. Complete the literature review, including the visual flow chart.
6. Conduct expert interviews and perform analysis to create the revised, modular test planning tool.
7. Using this tool, plan future tests of the re-designed prototype and communicate the plans with the design team, in order to influence the re-design for optimal testability.
8. Conduct tests of re-designed prototype and produce further design change recommendations.
9. Compare the efficiency of both iterations of prototype tests as per metric.
10. Assess the success of the test planning tool and make recommendations for its improvement.

Unfortunately, this process would only have been possible in an idealised world without time pressure. Given the time constraints of the NMT project, the design team began re-designing and developing the front end prototype immediately after completion of the field trials, which meant there would not have been time for steps 5 and 6 to be completed before step 7. With this in mind, the approach ultimately taken and presented in this thesis was the result of practical considerations, and albeit not ideal, achieved the aims set at the beginning of the project.

6.5 Conclusions

This thesis set out to aid in addressing the sanitation crisis, through planning and conducting prototype tests, thus generating data to inform the further development of the Nano Membrane Toilet, and by investigating and formalising how prototype tests are planned and conducted for the NMT and other novel, complex products. Both of these aims were achieved through the combined practical work in Chapters 2 and 4 and theoretical work in Chapters 3 and 5. The practical work yielded data on which to base design decisions, thus posing as two small cogs in the machinery that is the NMT project. The theoretical work combined the scattered and often tacit knowledge about testing prototypes into a holistic tool to develop visual testing strategies, thus providing the grease with which the NMT project and other PD endeavours will run more smoothly.

Before the field tests of Chapter 2, the mechanical flush developed by Tierney (2014) had only been tested in laboratories. Through tests with real faeces and real users, valuable information for the improvement of the NMT was generated and concrete design recommendations given that will make it a cleaner, better functioning and more user-friendly product. Additionally, knowledge was produced that could be useful for sanitation research as a whole, and that could validate and expand on existing research methodology and practice.

Chapter 4 generated valuable information for the development of the NMT's process control. Knowing how to best separate solids from liquids, and that this cannot be achieved by settling alone, will affect future design decisions for the NMT back end technology. Future research into the maceration of faeces and toilet paper in suspension as means to promote settling is recommended. Alternatively, the contact time between liquids and faeces in the NMT collection tank should be kept to a minimum.

Furthermore, the complicated process of planning, conducting, analysing, and communicating prototype tests was explored, not only for the NMT but for PD projects in general. While Chapters 2 and 4 provided first-hand experience of prototype testing, Chapters 3 and 5 explored theoretical, academic knowledge through literature review and the tacit practical knowledge of experts, to ultimately combine it into a simple tool to create visual testing strategies, which could benefit a variety of PD projects. Such a tool is unique in its application for prototype testing.

Future research efforts to attempt practical validation of the modular test planning tool and to work towards simplifying its use, for example by producing a simple, graphical software is suggested. Any tool that can facilitate and accelerate the development of complex, novel technologies addressing the dire state of sanitation across the globe should be promoted. Hopefully, the presented research made a small contribution toward this goal.

6.6 References

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